Forecasting Research

Forecasting Research Division
Technical Report No. 220

The Tile Surface Exchange Scheme: Performance within the Site Specific Forecast Model

by

M.J. Best, W.P. Hopwood and S.D. Jackson

July 1997

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Abstract

The Site Specific Forecast Model (SSFM) development project aims to develop a relatively inexpensive automated model to add site specific forecast skill to NWP products. The model is 1D based upon the UM 'physics' routines, with some small modifications, and driven by output from operational NWP product (currently only the mesoscale model, though this is not a restriction). This report contains results likely to form part of the report for stage 3 of the project plus additional work not applicable for inclusion in the stage 3 report. It concentrates on assessing the performance of the tile surface exchange scheme, an integral component of the second practical version of the SSFM described in the SSFM project stage 3 plan (the first practical version is discussed in Clark et al.; 1997).
It is anticipated that the tile surface exchange scheme will replace the current UM surface exchange scheme at version 4.4 as part of MOSES II. The difference between it and the current UM scheme is that each surface within a model grid-box has its own surface energy balance. The grid-box or effective parameters are derived by aggregating by land-use fractionthe tile prognostic and diagnostic variables. Currently the grid-box parameters are derived directly from effective variables.
The version of the SSFM used in this study was the first trial version (Clark et al., 1997)with modifications to replace the current UM surface exchange scheme with the tile surface exchange scheme. This development version has the following features:

i) Higher resolution in the boundary layer.
ii) Replacement of the existing UM surface exchange scheme with tiles.
iii) Treatment of alternative surface characteristics more appropriate to the site of interest rather then the mesoscale model grid-box value.
iv) Implementation of the MOSES soil/surface scheme, with its multi-level soil moisture scheme.
v) Coupling to mesoscale model output.

This development version has been tested for a number of idealised land-use configurations intercomparing with the corresponding evolution of the first trial version. In addition, for 3 real synoptic sites tests over a continuous 1 month period intercomparisons with the objectivestatistics obtained with the first trial version over the same period were performed.

The results show significant reductions in bias and RMS error for windspeed and screen temperature over the first trial version of the SSFM documented in Clark et al. (1997) and modest reductions when compared to the Mesoscale performance. This suggests a general improvement in forecast skill

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The tile surface exchange scheme: performance within the Site Specific Forecast Model

Summary

The Site Specific Forecast Model (SSFM) development project aims to develop a relatively inexpensive automated model to add site specific forecast skill to NWP products. The model is 1D based upon the UM 'physics' routines, with some small modifications, and driven by output from operational NWP product (currently only the mesoscale model, though this is not a restriction). This report contains results likely to form part of the report for stage 3 of the project plus additional work not applicable for inclusion in the stage 3 report. It concentrates on assessing the performance of the tile surface exchange scheme, an integral component of the second practical version of the SSFM described in the SSFM project stage 3 plan (the first practical version is discussed in Clark *et al.*; 1997).

It is anticipated that the tile surface exchange scheme will replace the current UM surface exchange scheme at version 4.4 as part of MOSES II. The difference between it and the current UM scheme is that each surface within a model grid-box has its own surface energy balance. The grid-box or *effective* parameters are derived by aggregating by land-use fraction the tile prognostic and diagnostic variables. Currently the grid-box parameters are derived directly from *effective* variables.

The version of the SSFM used in this study was the *first trial* version (Clark *et al.*, 1997) with modifications to replace the current UM surface exchange scheme with the tile surface exchange scheme. This *development* version has the following features:

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Contents

Introduction 2
The Tile Surface Exchange - A Review 3
First Trial and Development Version Model Description 9
Configuration 9
Vegetation Canopy 9
9 Soil Levels 10
Tile Surface Exchange 10
Initialisation 11
Forcing 11
Diagnostics 12
Idealised Intercomparison 12
Objectives 12
Procedure 12
Results 13
General Temperature Intercomparison 13
Impact of variation in land-use fraction on temperature evolution 14
Impact of variation in land-use fraction on windspeed and wind direction 16
Conclusions from idealised study 18
Trial Intercomparison 19
Objectives 19
Procedure 19
Verification against Observations 19
General Behaviour 20
Screen Temperatures - diurnal cycle 20
Screen Temperature - 12Z initialisation 21
Individual Site Behaviour 24
Screen Temperature 24
Tile Screen Temperature 28
10-metre Windspeed and Direction 34
Relative Humidity 39
Conclusion from objective statistics 42
Overall Conclusions 43
References 44

Introduction

The Site Specific Forecast model development project aims to develop a relatively inexpensive automated model to add site specific forecast skill to NWP products. The model is 1D based upon the UM 'physics' routines, with some small modifications, and driven by output from operational NWP product (currently only the mesoscale model, though this is not a restriction).

The development project is described in the PID (Clark, 1996). Stage 2 of the project (Clark *et al.*, 1997) involved the construction of the *first trial* version of the model and its testing. This version had the following features:

i Higher resolution in the boundary layer.
ii Improvements to the existing surface exchange formulation.
iii Treatment of alternative surface characteristics more appropriate to the site than the mesoscale gird-box value.
iv Implementation of the MOSES soil/surface scheme, with its multi-level soil moisture scheme and with the possibility of higher resolution in the soil temperature scheme.
v Coupling to the mesoscale output.

This version was successfully tested for 15 synoptic sites over a continuous 3 month period and is documented in Clark *et al.* (1997). The 3rd stage of the project concentrates on the implementation and assessment of the *second trial* version of the Site Specific Forecast Model which primarily includes a site specific implementation of local fetch characteristics, orography and, optionally, treatment of extremely local phenomena such as sheltering. The characterization of the 'site-specific' flow would be relatively straight forward over homogeneous terrain. However, natural terrain is rarely homogeneous, and heterogeneity may exist on numerous lengthscales. This simple observation implies that at any point within a large scale model grid-box the flow may have travelled across surfaces with significantly different characteristics than those that make up the gird-box mean surface. Therefore to describe the turbulent fluxes at a specific site within a grid-box requires the calculation of upwind spatial or 'area-average' fluxes of momentum, heat and moisture for which Monin-Obukhov similarity is still valid.

The surface turbulent fluxes are currently calculated in the Unified Model (UM) from a surface roughness length for each transfer process, $z_{0(m,t,q)}$, based upon the Institute of Terrestrial Ecology 10km dataset, that is aggregated to form effective values according to the proportion of each type of land-use within the model grid-box. There are two disadvantages to this approach, firstly each land-use types over which the aggregation takes place are assumed to have the same stability which need not be true and secondly, isotropy is imposed so that the diagnosed surface turbulent fluxes are constant with position throughout the grid-box, invariant with upwind fetch from any position within the model grid-box and no account of the 'site-specific' flow contribution is made. The latter is remedied by the introduction of *Directionally Dependent Fetch* (DDF) to be discussed in a later paper. However the solution to the former requires the implementation of a tile surface exchange scheme (Jackson, 1995).

This report documents the performance of the tile surface exchange scheme compared to the existing scheme by implementing the tile code within the *first trial* version of the SSFM to form the so-called *development* version. In this version it must be emphasised that no account has been taken of sub-mesoscale grid orography which will be addressed in subsequent *development* versions. In order to assess the impact of implementing the tile scheme a number integrations were performed using idealised land-use configurations but, to further assess the likely benefit of using the tile scheme as opposed to the current UM surface exchange scheme, tests at 3 synoptic sites over a continuous 1 month period with objective verification against observations were performed. The sites chosen for this part of the study were:

Beaufort Park	03763	51.38N	0.78W
Heathrow	03772	51.48N	0.45W
Gatwick Airport	03776	51.15N	0.18W

Prior to results from the intercomparisons being shown it is worth reviewing the tile surface exchange scheme.

The Tile Surface Exchange - A Review

The tile approach calculates the fluxes in the surface layer independently on a land-use patch -by-patch basis over land. Its main benefit over effective parameters is in regions where stability differs between land-use patches (tiles). In order for the tile approach to work a couple of assumptions have to be made; firstly, that each patch interacts independently with the atmosphere just above it and that fluxes from each tile are mostly vertical and not horizontal *i.e.* the implication that the surface layer above each tile is in equilibrium with the tile surface. And secondly that the large scale flow above each tile in the fetch is the same so that Monin-Obukhov similarity can be invoked.

In order to get the correct fluxes for each tile the surface layer gradients have to be known. For winds, the lower boundary condition is straightforward, since we assume the no-slip condition at the surface. For temperature, as the tiles are independent and hence have different energy balances, each tile will have a separate T_*. As q_* can be derived from T_* it is also tiled (Note: the normal boundary layer convention is used not the normal UM one). What is needed is the gradient between the tile surface and the tile level 1, but the model has the tile surface and the gird-box level 1 (see Figure 1). Hence the level 1 values of wind, temperature and humidity need to be adjusted to the local tile profiles in order to calculate the tile surface layer gradients. This can be

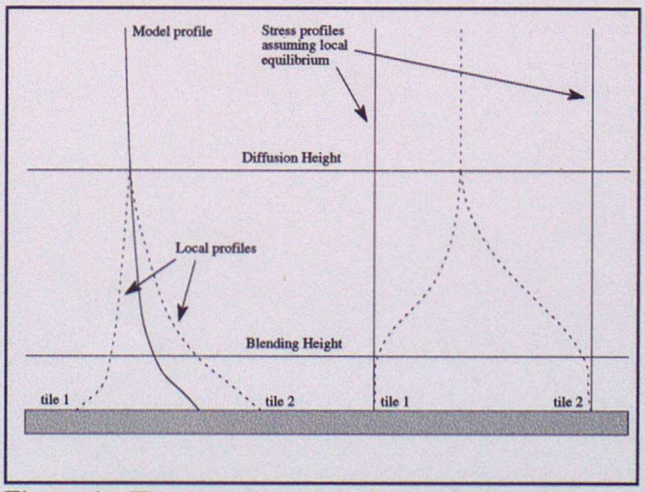

Figure 1 - The deduction mean flow and flux profiles from the local flow and fluxes profiles.

accommodated by calculating a parameter akin to the 'wind profile factor' currently used in the interpolation of 10m winds where the tile profile is adjusted rather than the local one. To get good estimates of the tile gradients and stabilities requires variables that are not *a priori* to the scheme and have yet to be calculated. This implies an iterative approach.

Before this iterative approach is considered it is worth noting that the tile scheme can be combined with the effective roughness scheme for sub-grid scale orography such that: For each tile in an upwind fetch (defined by the large scale flow), the local roughness lengths for heat and momentum are included from a look-up table. The effective momentum roughness length for the i^{th} tile, $z_{0m}^{eff,\,i}$, can be calculated by averaging the shear stress at the orographic blending (or combination) height, z_c to give,

$$\frac{k^2}{\left[\ln\left(\frac{z_c}{z_{0m}^{eff,i}}\right)\right]^2} = \frac{1}{2} D \frac{A}{S} f_D(Ri_b) + \frac{k^2}{\left[\ln\left(\frac{z_c}{z_{0m}^{i}}\right)\right]^2} \qquad (1)$$

where D is the orographic drag coefficient (typically ~0.3; Marshall, 1971). For heat and moisture, transport away from the surface is assumed to be unaffected by the form drag of the unresolved orography, and is only dependent on the land-use. Hewer and Wood (1996) find this true for moderate slopes (>18°), but there is an increase in z_{0h} for steep slopes. However to 1st order using the local roughness is a reasonable approximation in the absence of such a parametrization, thus z_{oh} is taken to be $0.1z_{0m}$.

The iteration is initiated by taking the gradient and stability over the whole depth of the tile, that is from the surface to the blending height l_b. As a first guess to the profile for each tile the neutral profile suggested by Claussen (1991) is chosen such that,

$$T(l_b) - \bar{T}_* = (\bar{T}_1 - \bar{T}_*) \frac{\ln(l_b/z_{0h})}{\ln(z_1/z_{0h})} \qquad (2)$$

$$u(l_b) = \bar{u}_1 \frac{\ln(l_b/z_{0m}^{eff})}{\ln(z_1/z_{0m}^{eff})} \qquad (3)$$

From these an adjustment factor can be calculated for each tile to convert the grid-box level 1 values to an estimate of the *tile* value. This in turn gives a better estimate of the surface layer gradient, bulk Richardson number and thus the tile level 1 values. This method gives

a reasonable estimate of the tile layer stability without loss of vertical resolution. It differs from Claussen's (1991) approach where the tile stabilities are only calculated over the bottom model layer. It can be shown that, using a similar method to the interpolation of screen temperature and 10m winds, the equations (4), (5) and (6) can be used to estimate level 1 tile values from the mean profile, where the overbars represents a grid-box value from the mean profile and non-overbar refer to the tile values. These level 1 values are then used to calculate the surface layer gradients as in the non-tile scheme. Since interpolation is being carried out from the blending height, prognostic variables at this height are needed. These could be found by interpolating from the two adjacent layers to l_b or just simply taking the nearest model level. As it has already been asserted that l_b is a heuristic parameter of $O(1)$ then the pragmatic approach can be taken in choosing the model level below l_b as this avoids an unwanted *loss* in vertical resolution.

$$u_1 = u_0 + \frac{\ln(l_B/\bar{z}_{0m}^{eff})}{\ln(l_B/z_{0m}^{eff})} \frac{\Phi_m(\zeta_1,\zeta_{0m}^{eff})}{\Phi_m(\zeta_{l_B},\bar{\zeta}_{0m}^{eff})} \left[\bar{u}(l_B) - u_0 \right] \tag{4}$$

$$T_L(z_1) = T_* - \frac{g}{c_p} z_1 + \frac{\ln(l_B/\bar{z}_{0h})}{\ln(l_B/z_{0h})} \frac{\Phi_h(\zeta_1,\zeta_{0h})}{\Phi_h(\zeta_1,\bar{\zeta}_{0h})} \left[\bar{T}_L(l_B) - T_* + \frac{g}{c_p}(l_B - z_{0h} + z_{0m}^{eff}) \right] \tag{5}$$

$$q_t(z_1) = \bar{q}_t(l_B) + \psi \frac{\ln(l_B/\bar{z}_{0h})}{\ln(l_B/z_{0h})} \left(\frac{\Phi_h(\zeta_1,\zeta_{0h})}{\Phi_h(\zeta_1,\bar{\zeta}_{0h})} - 1 \right) \left[\bar{q}_t(l_B) - q_{sat}(T_*,p_*) \right] \tag{6}$$

From here, calculating the tile surface fluxes is straightforward such that the explicit flux for surface tile j can be written as,

$$\frac{H_j^n}{c_p} = \rho K_{PM_j} (R_j - L_c \rho K_{E_j} \Delta q_{1_j}) \tag{7}$$

and,

$$E^{n}_{*_j} = \psi_j \, \rho K_{PM_j} [\alpha_{1_j} R_j + (c_p \, \rho K_{H_j} + A_{*0}) \, \Delta q_{1_j}] \tag{8}$$

where

$$\rho K_{PM_j} = \frac{\rho K_{H_j}}{(L_c \, \alpha_{1_j} \psi_j + c_p) \, \rho K_{H_j} + A_{*0}} \tag{9}$$

$$A_{*0} = \frac{2\lambda_{soil}}{\Delta z_1} \tag{10}$$

$$R_j = R_{N\downarrow *0} - A_{*0} \left[T^{n}_{L_1} - T^{n}_{s_1} + \frac{g}{c_p} (z_1 + z_{0m_j} - z_{0h_j}) \right] \tag{11}$$

$$\Delta q_{1_j} = q_{sat}(T^{n}_{L_1}, p_*) - q^{n}_{W_1} + \alpha_{1_j} \frac{g}{c_p} (z_1 + z_{0m_j} - z_{0h_j}) \tag{12}$$

and

$$\rho K_{E_j} = \psi_j \rho K_{H_j} \tag{13}$$

Once the tile fluxes have been deduced, they can be area-averaged in the following way (Wood and Mason, 1990; Hopwood, 1995),

$$\overline{c_D U(z)^2} = \overline{u_*^2} = \kappa^2 U^2(l_b) \left(\ln \left(\frac{l_b}{z_{0m}^{eff}} \right) + \psi \left(\frac{l_b}{L_M} \right) \right)^{-2} \tag{14}$$

$$\overline{\theta(l_b) - \theta_*} = \frac{\kappa H}{U_*}\left(\ln\left(\frac{l_b}{z_{0h}}\right) + \psi\left(\frac{l_b}{L_M}\right)\right)^{-1} \quad (15)$$

to give mean fetch or grid-box flux, which is then used as input into the boundary layer mixing scheme. However, the subsequent boundary layer mixing will affect the gradients in the surface layer so that the surface fluxes will have to be corrected to allow for it. This is done on a tile-by-tile basis so that the flux can be re-averaged. The implicit fluxes for surface tile j are,

$$\frac{H_{*_j}}{c_p} = \frac{H_{*_j}^{\,n}}{c_p} + \gamma_1 \rho K_{PM_j}[\rho K_{E_j} L_c(\delta q_{W_1} - \alpha_{1_j}\delta T_{L_1}) - A_{*0}\delta T_{L_1}] \quad (16)$$

and

$$E_{*_j} = E_{*_j}^{\,n} + \gamma_1 \psi_j \rho K_{PM_j}[c_p \rho K_{H_j}(\delta q_{W_1} - \alpha_{1_j}\delta T_{L_1}) - A_{*0}\delta q_{W_1}] \quad (17)$$

where the implicit equation for δT_{L1} is,

$$A_{T_1}\delta T_{L_2} + B_{T_1}\delta T_{L_1} + C_{T_1}\delta q_{W_1} = \delta T_{L_1}^{\,n} \quad (18)$$

where

$$\delta T_{L_1}^{\,n} = \left(\frac{g\delta t}{\Delta p}\right)\left[F_{T_L}^{\,n}(2) - \sum_j f_j \frac{H_{*_j}^{\,n}}{c_p}\right] \quad (19)$$

$$C_{T_1} = \gamma_1\left(\frac{g\delta t}{\Delta p}\right) L_c \sum_j f_j \rho K_{PM_j} \rho K_{E_j} \quad (20)$$

and

$$B_{T_1} = 1 - A_{T_1} - \gamma_1\left(\frac{g\delta t}{\Delta p}\right)\sum_j f_j(L_c \alpha_{1_j} \rho K_{E_j} + A_{*0})\rho K_{PM_j} \quad (21)$$

and the implicit equation for δq_{w1} is,

$$A_{q_1} \delta T_{L_1} + B_{q_1} \delta q_{W_1} + C_{q_1} \delta q_{W_2} = \delta q_{W_1}{}^{n} \tag{22}$$

where

$$\delta q_{W_1}{}^{n} = \left(\frac{g \delta t}{\Delta p} \right) \left[F_{q_W}{}^{n}(2) - \sum_j f_j E_{*_j}{}^{n} \right] \tag{23}$$

$$A_{q_1} = \gamma_1 c_p \left(\frac{g \delta t}{\Delta p} \right) \sum_j f_j \alpha_{1_j} \rho K_{PM_j} \rho K_{E_j} \tag{24}$$

and

$$B_{q_1} = 1 - C_{q_1} - \gamma_1 \left(\frac{g \delta t}{\Delta p} \right) \sum_j f_j (c_p \rho K_{H_j} + A_{*0}) \psi_j \rho K_{PM_j} \tag{25}$$

Tile surface temperatures can be deduced from the assumption of a surface energy balance and solving the Penman-Monteith equation. These are updated in the calculation of the surface evaporation together with the calculation of screen diagnostics. In using a tile scheme some thought has to be put into deciding which screen diagnostics are the most representative. To compare with observations, assuming a *short grass* tile may be the most appropriate since observing sites tend to be on short grass. However not all fetches/grid-boxes will have significant proportions of short grass so the dominant surface may be more suitable. Another possibility is to use an averaged surface. This is probably best decided by choosing the method that verifies the best since these are only diagnostics. A future paper will discuss the merits of a aggregated screen temperature diagnostic based upon a source area model to deduce the correct upwind fetch characteristics that contributes to the screen temperature.

First Trial & Development Version Model Description

Configuration

A number of different configurations of model physics were run for comparison. The base configuration was denoted 'as per mesoscale' (APM) in that the intention was to produce, as far as possible, the same results as the operational mesoscale configuration. This was run in order to demonstrate that differences from the mesoscale model are due to real changes in physics or surface conditions and not simply numerical differences, the mode of running or coupling in the model.

The APM configuration used the same physics and resolution as the mesoscale model. Soil, vegetation and orographic roughness parameters were derived from the mesoscale fields by bi-linear interpolation to the site in question. The first two actually vary very little over the mesoscale domain and the orographic roughness is relatively small and smooth for the sites considered.

A timestep of 100s was used with the radiation called every 5 minutes. This differs from the true Mesoscale (physics timestep every 5 minutes) but Clark *et al.* (1997) showed that it is indistinguishable from running with longer timesteps however this difference should be kept in mind. As was noted in Clark *et al.* (1997) it is impossible to run exactly as the mesoscale, as we initialize from the mesoscale analysis. In the full model, data assimilation continues for two hours while here no data are assimilated. This additional data assimilation does have impact via the forcing data, but the absence of a small amount of assimilation should be expected to have a short lived impact. It is also impossible to run with exactly the same ozone distribution, as the facility to run with a limited number of ozone layers is not available in the single column UM (USCM). These differences are small but emphasize the need to have successfully compared the model run APM with the mesoscale model itself in Clark *et al.* (1997).

All *first trial* and *development* versions of the SSFM were built as recommended by Clark *et al.* (1996). All configurations had 70 levels, with all the resolution enhancement in the bottom 2km (i.e. the boundary layer levels), which had 53 levels. All configurations incorporated MOSES I, the new Met. Office Surface Exchange Scheme, that implements multi-layer hydrology with soil moisture freezing and Penman-Monteith surface exchange with an interactive vegetation model; Monin-Obukhov (MO) surface exchange; no RMBL and diagnostic convection. A few optional components were varied in order to assess their impact to performance changes in the idealised and trial intercomparisons. These were:

Vegetation canopy

The simple radiative canopy model is described in Clark *et al.* (1996). It is used in the idealised intercomparisons for versions with and without the canopy. The use of the vegetation canopy scheme in conjunction with the tile surface exchange scheme requires thought as to its applicability over different land-use surfaces. For example, it would not be applicable over a bare soil surface. Therefore, when used with the tile scheme, only the vegetative tiles were coupled to the canopy model.

9 Soil levels

The MOSES I scheme is generally run with four soil levels, but it has been shown (Clark *et al.*, 1996) that with sufficiently small timestep it can be run with greater soil resolution. Clark *et al.* (1996) showed that a better simulation of soil temperatures could be achieved with nine levels.

Tile Surface Exchange

Independent land-use tiles for seven types of surface: deciduous trees, coniferous trees, C3 grass, C4 grass, bare soil, urban and open water.

The *first trial* versions used in the idealised intercomparison are configurations with and without the *vegetation canopy*, without *9 soil levels* and of course without the *tile surface exchange*.

The *development* version used in both the idealised and trial intercomparisons was a configuration with the *vegetation canopy* and *tile surface exchange* but without *9 soil levels*.

Apart from the above, and the minor differences in the ozone already noted, other aspects of the model were 'as per mesoscale'. The same critical RH was used in the cloud scheme, though interpolated in the boundary layer. Hence Table I summarises the combinations used in the two intercomparisons:

Table I

Decimal Code	Configuration	Intercomparison
M00000	Standard Mesoscale	Trial
S00093	MOSES + No RMBL + MO surface exchange + No convection + 9 soil levels	Trial
S00095	MOSES + No RMBL + MO surface exchange + No convection + Veg canopy + 9 soil levels	Trial
S00159	MOSES + No RMBL + MO surface exchange + No convection + Veg canopy + tiles	Trial + Idealised
S00029	MOSES + No RMBL + MO surface exchange + No convection	Idealised
S00031	MOSES + No RMBL + MO surface exchange + No convection + Veg canopy	Idealised

Initialisation

The initial data for each run have been derived in two different ways. The first is to derive the data directly from the mesoscale analysis. The prognostic variables are simply interpolated (in log pressure) to the required levels. There are problems for the soil variables, as, currently, the mesoscale runs with different soil temperature levels and only one soil moisture level. Soil temperature has been dealt with by interpolation assuming an exponential change with depth from one level to the next, the rate of change depending on mesoscale soil characteristics. Below the bottom mesoscale level the temperature was assumed constant. Analysis of continuous runs in Clark *et al.* (1997) suggested that a linear interpolation between the last but one and last level would have been more appropriate, but this has negligible impact on short runs.

Soil moisture was generated in the multi-level scheme by assuming a constant soil moisture stress (i.e. the difference between the SMC and wilting SMC divided by the difference between the critical SMC and wilting SMC) equal to that in the mesoscale soil layer. It is impossible to derive an accurate conversion between the two schemes, particularly as we expect a different SMC evolution from MOSES, but this method tends to produce the same evapotranspiration as the single level scheme. It should also be born in mind that in MOSES the soil thermal properties take soil moisture into account, so there is a coupling between the two schemes.

In order to retain soil temperature and moisture structure, especially when the nine level scheme is used, runs also were performed using the T+6 forecast from the previous run as initial data. Thus, soil moisture and temperature are allowed to free run, and the mesoscale analysis only influenced evolution via the forcing data. This may be thought of as the first step towards a *data assimilation* scheme, running in continuous mode. It is also a potential mode of operation for sites without observations. The two modes of operation were denoted *M* and *S*, i.e. initialized from the mesoscale or SSFM.

Forcing

As the USCM contains the physics of the full UM, it could be forced using the total dynamical tendencies from the large scale model. However it is difficult to extract the large scale dynamical tendencies even when runs are set up with the sole purpose of doing so. Considering the SSFM is constrained to forcing runs with routinely available NWP output an approximate approach is required that follows the large scale forcing but is also able to introduce realistic local variation. To this end Clark and Dunlop (1997) have designed and tested a simple forcing system based upon the UM dynamics that the integrations conducted in these intercomparisons have harnessed. See Clark and Dunlop (1997) or Clark *et al.* (1997) for further details.

Diagnostics

The inclusion of the tile surface exchange scheme required some work to be done on producing tile screen level temperatures and grid-box average screen level temperature as output diagnostics. Previously the only screen level tile diagnostic was the screen temperature over the grass tile, deemed as being representative of an enclosure site. Subsequent reports will show that this need not be the case. Additionally work was done on the visibility diagnostic to update it to the new scheme documented in Wright (1997). Also the NIMROD gust, cloud, precipitation type, lightning and standard UM cloud diagnostics were included.

Idealised Intercomparison

Objectives

The objectives of performing an idealised intercomparison were as follows:

1. To demonstrate that the tile scheme could run within the high resolution SSFM framework.
2. To show that the tile scheme's response to the idealised variation in land-use fraction is consistent with the aggregation theory of Mason (1988).
3 To assess the impact of only tiling the atmosphere surface exchange and not the soil below.

Procedure

The comparison of the *first trial* (no tiles) and *development* (tiles) versions of the SSFM was achieved by intercomparing the near surface winds and temperatures for imposed land-use fractions of 100% bare soil, 75:25 bare soil : C3 grass, 50:50 bare soil : C3 grass, 25:75 bare soil : C3 grass and 100% C3 grass. Specifically for temperature: the first level soil temperature T_{s1}, surface temperature T_*, diagnosed screen (1.25m) temperature $T_{1.25}$ and level 1 temperature T_1; and for wind: the diagnosed 10m windspeed and direction. This was done for the radiation night case of the evening of 7th November 1996 chosen from the Autumn 1996 trial (Clark *et al.*, 1997) initialised from 12Z on that day and integrating until 6Z the following morning.

Results

The results are divided into three sub-sections: general temperature intercomparison, which gives a initial indication of the performance of the *development* version compared to the existing *first trial* version; impact of variation in land-use fraction on temperature evolution, which addresses the performance with respect to varying surface and; impact of variation in land-use fraction on windspeed and direction.

General temperature intercomparison

Figures 2 and 3 shows an intercomparison of the *first trial* and *development* versions run with first a 100% bare soil surface and then with a 100% C3 grass surface. The agreement is good with the differences in the diagnosed screen temperature being attributable the implementation of a new interpolation scheme based upon Monin-Obukhov similarity. These results show that the tile scheme is constant with the current surface exchange scheme.

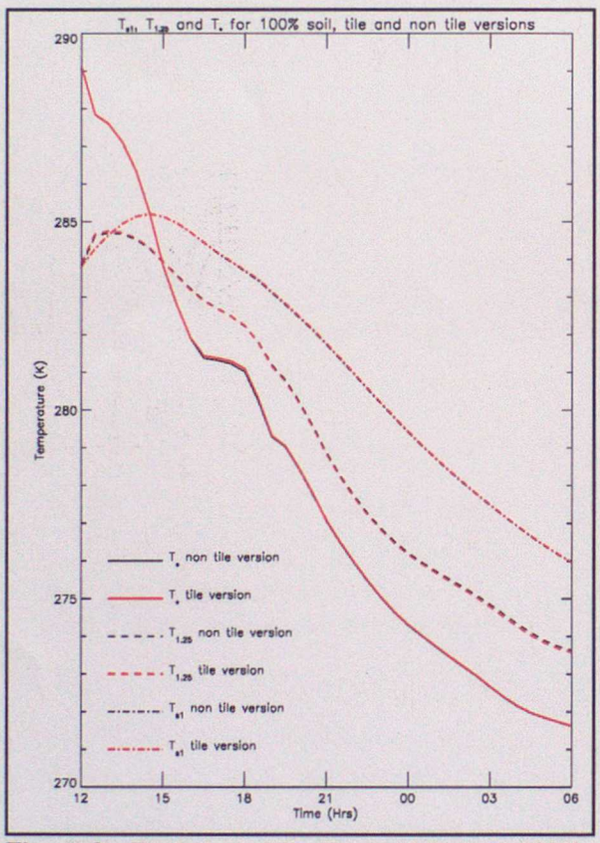

Figure 2 - Evolution of T_{s1}, $T_{1.25}$ and T_* for a 100% bare soil surface. See key on plot.

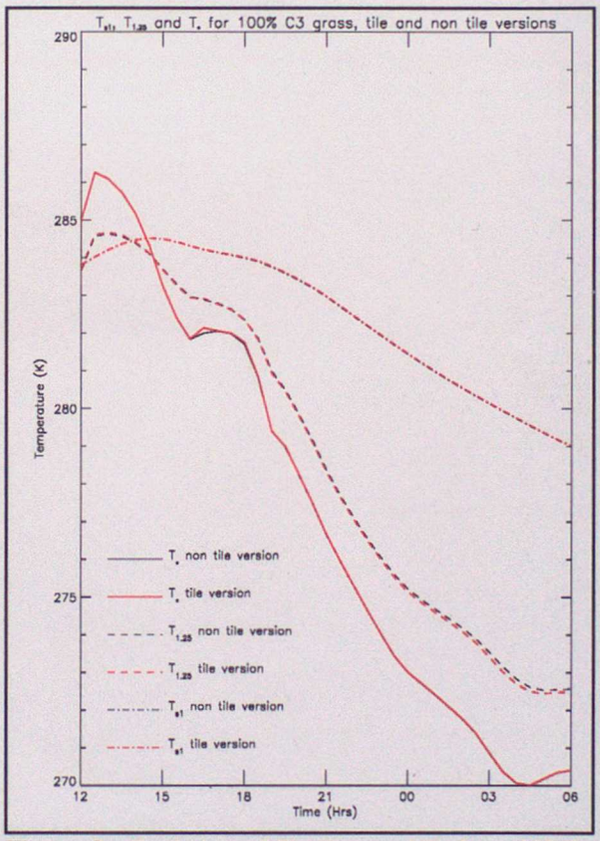

Figure 3 - Evolution of T_{s1}, $T_{1.25}$ and T_* for a 100% C3 grass surface. See key on plot.

Impact of variation in land-use fraction on temperature evolution

Figure 4 shows the soil level 1 temperature evolution for the *development* (with tiles) model with varying fractions of bare soil and C3 grass. Also shown (in dashed lines) are the corresponding fraction averaged soil temperatures from the 100% bare soil and 100% C3 grass temperatures. Generally the first soil level temperature increases with increasing C3 grass fraction due to the insulating effect of the Best (1996) vegetation canopy. However the plot does show small differences between the soil temperature for a given fraction of bare soil and C3 grass and that deduced from a land-use weighted fraction of the soil temperatures from surfaces of 100% bare soil and 100% C3 grass.

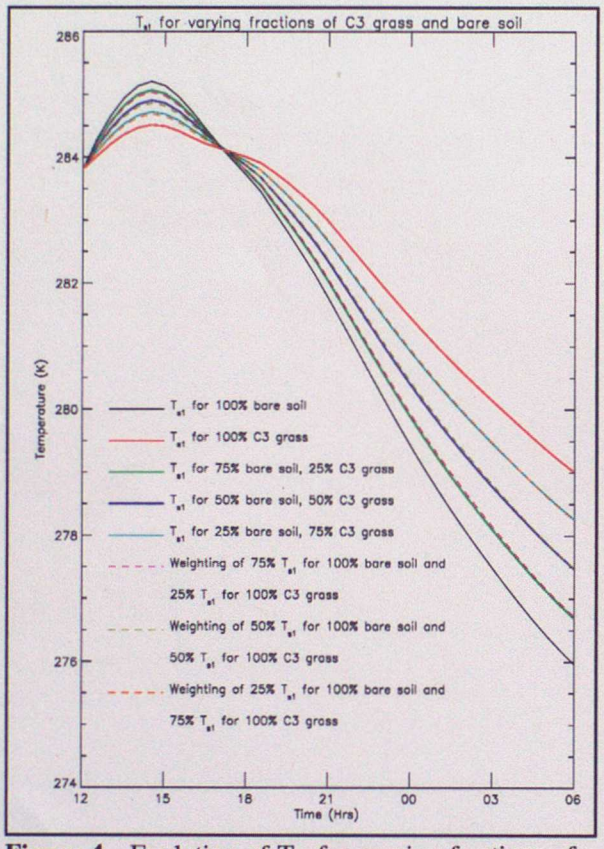

Figure 4 - Evolution of T_{s1} for varying fractions of bare soil and C3 grass. See key on plot.

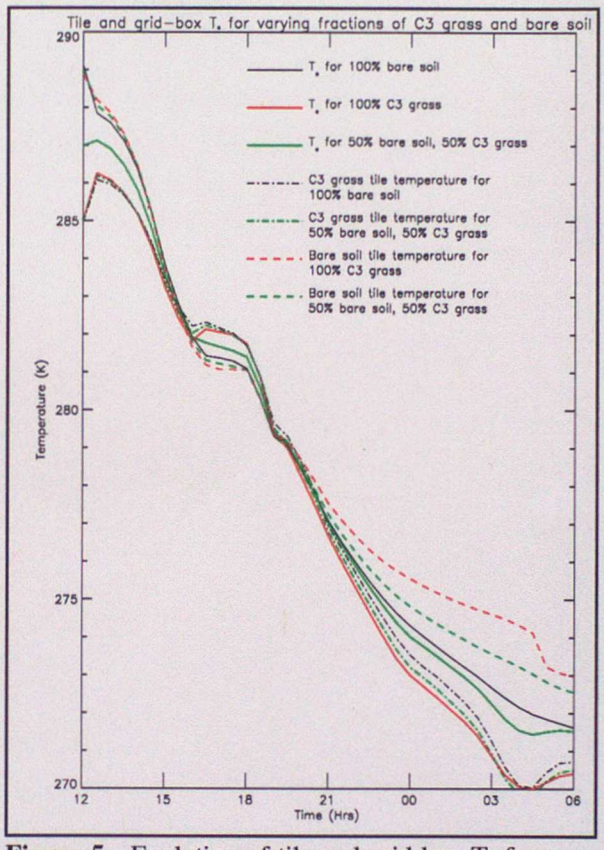

Figure 5 - Evolution of tile and grid-box T_* for varying fractions of bare soil and C3 grass for the *development* version

This shows that in the *development* version (tiles) the coupling between the surface and the first soil level is reasonable with the differences between it and the *first trial* version (no tiles) possibly being attributable to the non-tiling of the soil. Further evidence of this can be seen in Figure 5 which shows the tile surface temperatures over bare soil and over C3 grass, plus the grid-box surface temperature for various fractions of bare soil and C3 grass. On first inspection the 50:50 bare soil to C3 grass fraction has a grid-box surface temperature

evolution that is between the evolution for 100% bare soil and that for 100% C3 grass. Surprisingly however a more detailed analysis reveals that it is closer in absolute terms to the 100% bare soil evolution than to the 100% C3 grass evolution, when it would be expected to be equally weighted between them.

This can be explained in terms of the strength of coupling between the bare soil surface and the first soil level and that between the grass surface and the first soil level, which includes the canopy scheme. On its own the bare soil surface temperature is a diagnostic calculated from the first soil level temperature by a notional conductive coupling. As can be seen from Figure 4 the first soil level temperature increases with increasing fraction of C3 grass, an influence attributable to the soil not being tiled and the interaction offered by the vegetation canopy over the grass tile (Best, 1996) to the underlying soil. The canopy scheme acts to weaken the coupling between the surface and the first soil level so that it becomes a radiative and conductive admixture. The impact is that surface temperature of the bare soil tile for an integration performed with 100% C3 grass is a 1-2K warmer than for an integration performed with 100% bare soil. However for a grass surface the coupling between the first soil level temperature and the canopy temperature is always radiative and weak, therefore altering the proportion of C3 grass has only a small impact (~0.1K) on the grass surface temperature. Therefore the grid-box surface temperature, when aggregated correctly, is an average of a *warmer* diagnosed soil surface temperature with an unchanged grass surface

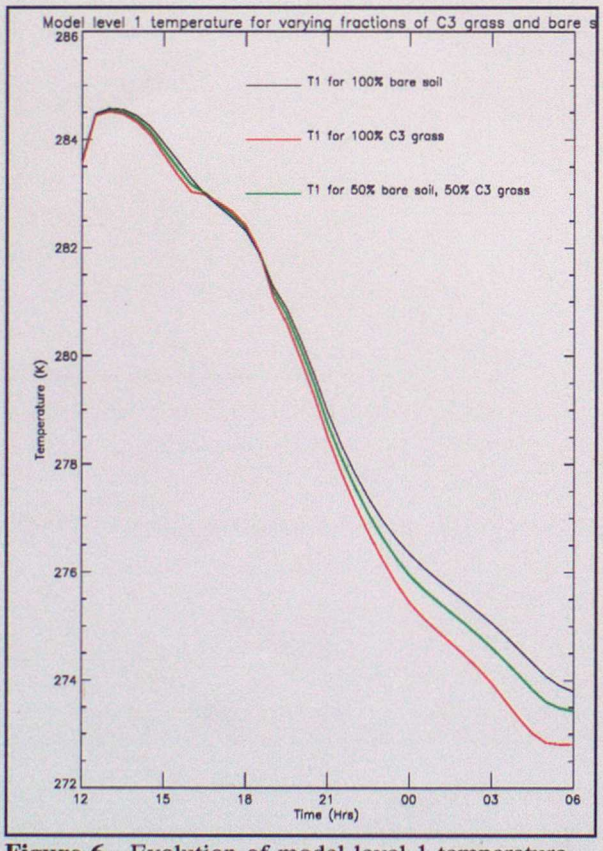

Figure 6 - Evolution of model level 1 temperature for 100% bare soil, 100% C3 grass and 50:50 bare soil to grass.

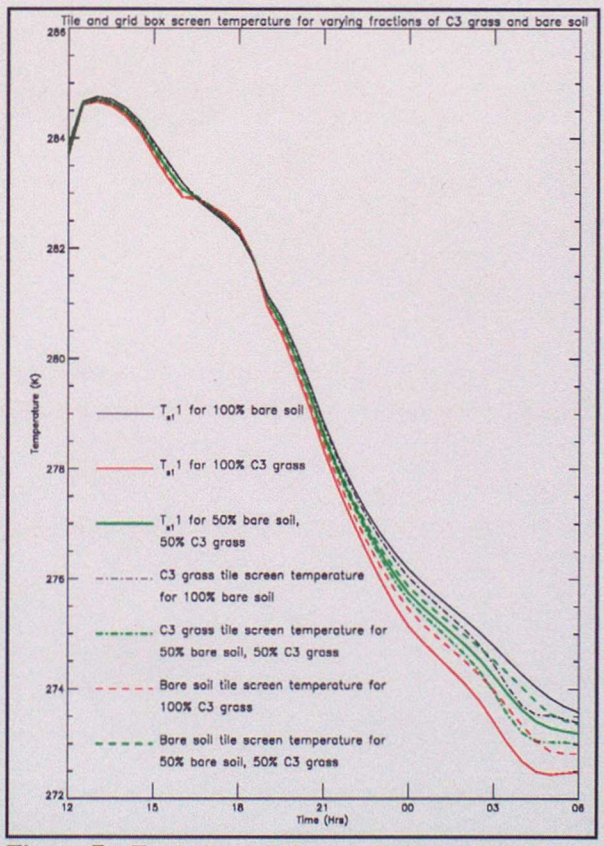

Figure 7 - Evolution of diagnosed tile and gird-box screen temperature for varying fractions of bare soil and C3 grass. See key on plot.

temperature. This yields an aggregated surface temperature that is closer to the soil tile surface temperature for a 100% bare soil surface than to the C3 grass surface temperature for a 100% C3 grass surface.

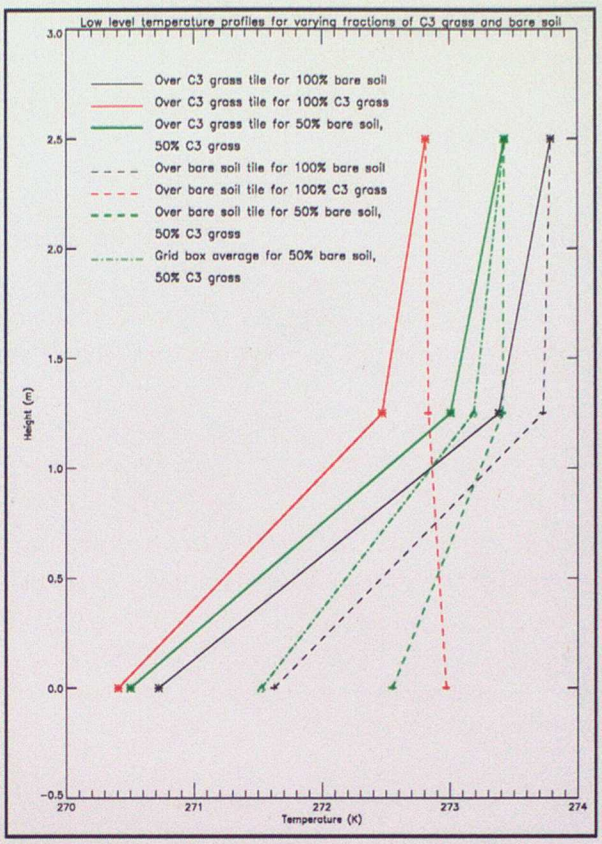

Figure 8 - Low level temperature profiles for surface, screen level and model level 1. See key on plot.

Figure 7 shows the diagnosed screen (1.25m) temperatures for various fraction of surface cover. These are derived by interpolation from the model level 1 temperature, shown in Figure 6, and the surface temperature using Monin-Obukhov similarity rather than the current UM scheme. The significance of these two plots can be best seen when viewed in conjunction with Figure 8, showing the lower surface layer profile over the bare soil and C3 grass tiles. The behaviour is very similar to the model level 1 behaviour where the 50:50 fraction is almost the weighted fraction of the 100% bare soil and 100% C3 grass model level 1 temperatures with the influence of the vegetation canopy only producing a slight contamination in the apparent weight. This slight contamination, compared to the large induced change in bare soil tile surface temperature with increasing grass fraction, is because the imposed similarity lapse between the surface and model level 1 implies most of the lapse occurs below screen height. For example, model level 1 at 2.5m, z_{oh} equal to 0.001m, then 91% of the surface to level 1 temperature lapse occurs below the screen height. If one assumes that the appropriate screen temperature diagnostic is the grid-box screen temperature, then the error in the canopy contaminated value compared a true aggregated value is ~0.05K, acknowledging the assumption that a similarity profile has been imposed within the roughness sub-layer. According to Garratt (1978) the error in this assumption is small for pseudo-homogeneous surfaces.

Further examination of Figure 8 shows that the influence of the grass vegetation canopy on the bare soil tile surface temperature with increasing grass fraction results in near surface layer above the bare soil tile becoming relatively unstable.

Impact of variation in land-use fraction on windspeed and direction

Figure 9 shows the 10m windspeed evolution for the *development* (tiles) version for various fractions of bare soil and C3 grass. It shows that the tile scheme is correctly aggregating the drag based upon the logarithmic average of the tile drag coefficients as documented in Mason (1988) and shown in equation (7).

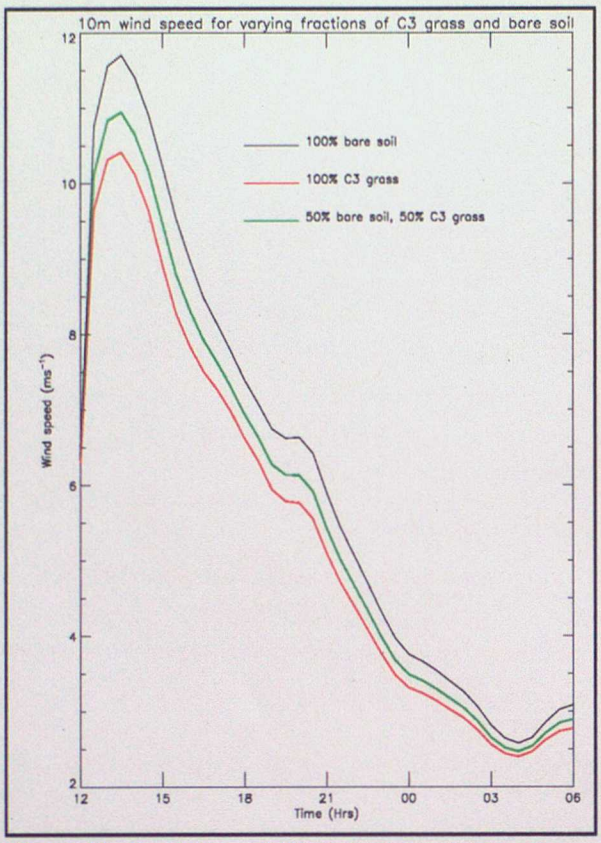

Figure 9 - Evolution of 10m windspeed for various fractions of bare soil and C3 grass. See key on plot.

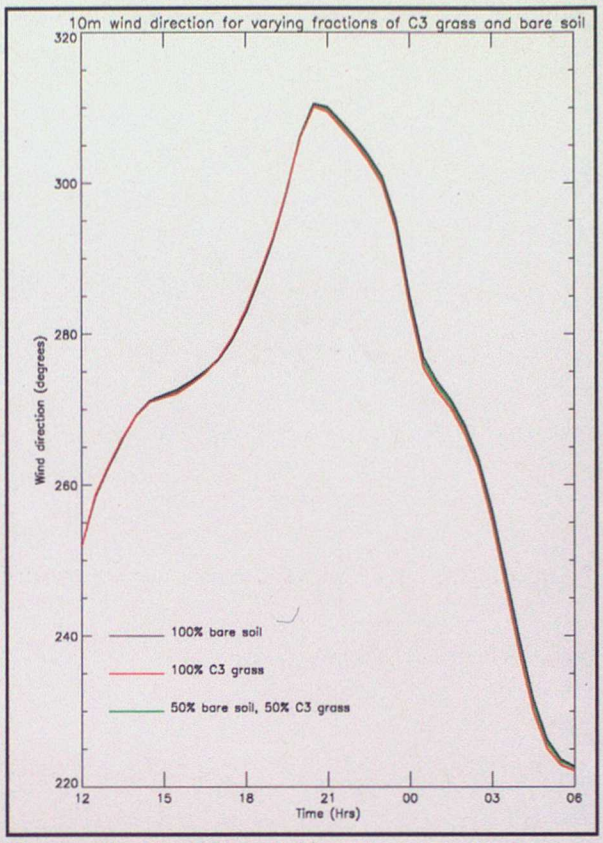

Figure 10 - Evolution of 10m wind direction for various fractions of bare soil and C3 grass. See key on plot

Figure 10 shows the 10m wind direction evolution for the *development* (tiles) version for various fractions of bare soil and C3 grass. The behaviour in consistent with the assertion that the surface drag has been correctly aggregated as there is little directional variance with land-use fraction.

Conclusions from the Idealised Study

1) It has been demonstrated that the tile scheme can run within the framework of the high resolution SSFM.

2) It has been shown that the general behaviour of the tile scheme, within the SSFM, to varying land-use fraction is consistent with the aggregation theory of Mason (1988) and its validations by Grant and Mason (1990) and Hopwood (1995).

3) There is evidence that tiling the surface in the *development* version, that also contains the vegetative canopy scheme, without tiling the underlying soil has an impact on the evening transition cooling rate. This is due to the interaction of the surface-atmosphere coupling strength over vegetative tiles, that include the canopy scheme, and the non-vegetative tiles with the first soil level temperature.

4) The impact of not tiling the soil on the overall error in diagnosed screen temperature was estimated to be approximately 0.05K which, anticipating later results, is about 5% of the typical site screen temperature error. This is small but significant compared to the improvements in the error.

5) Not tiling the soil has a large effect on the tile surface temperature, particularly over bare soil tiles where the difference with current scheme is about 1K.

Trial Intercomparison

Objectives

The objectives of performing a trial intercomparison were as follows:

1. To demonstrate that the tile scheme could be run routinely from coupled mesoscale model data.
2. To assess the impact of using the tile surface exchange scheme rather than the current scheme on forecast skill, both objectively and subjectively. Tests would concentrate on screen temperatures and wind.

Procedure

The trial was run exclusively on the HP fr1400 workstation using the archive of rerun and forcing data built up during the Autumn 1996 trial documented in Clark *et al.* (1997) for the month of November. Runs were performed at 00Z, 06Z, 12Z and 18Z from the appropriate data to a forecast time of T+18 for logistical reasons discussed in Clark *et al.* (1997). Hence the overnight forecast of minimum temperatures will be based on the 12Z run rather than the 06Z run applicable to Open Road. The improvement in forecast between 06Z and 12Z is on a scale unrelated to the changes that have been made here to the model physics. The diagnostic output was channelled into a single SAS dataset.

Verification against Observations

A statistical analysis of the performance of the *development* (with tiles) version of the Site Specific Forecast Model (SSFM) during a one month trial from 1st November 1996 to 30th November 1996 is presented. Comparison is made between the *as-per mesoscale* (APM, M00000) configuration of the Single Column Model, its suitability as the standard was assessed in Clark *et al.* (1997), the two best *first trial* (no tiles) version of the SSFM and the *development* (with tiles) version. One *first trial* configurations (S00093) represented a bare soil type surface by not including the vegetation canopy scheme (Best, 1997) and one (S00095) represented a grassy surface by including the vegetation canopy scheme. These configurations are documented in Table I. Comparisons were performed between the general performance with initialisation time and the detailed performance of integrations conducted from a 12Z initialisation time.

Means and RMS errors, that is the mean and RMS of the difference between model and observational data, in wind direction and speed, screen temperature and relative humidity were calculated. Also the statistics for the tile screen temperatures for the *development* version were calculated

Three observational sites were chosen:

Beaufort Park	03763	51.38N	0.78W
Heathrow	03772	51.48N	0.45W
Gatwick Airport	03776	51.15N	0.18W

It should be noted that screen temperature in the APM is assessed at being at 1.5m above the underlying surface, compared to the set screen height of 1.25m in the *first trial* and *development* versions, which is more representative of the true screen temperature, though the difference is small (see Figure 8 for example).

General Behaviour

Screen Temperature - diurnal cycle

Results from comparisons between the *first trial* configurations, the APM and the *development* version of the SSFM are shown in Figure 11. Here the biases and RMS errors over the 3 stations chosen from the 00Z and 12Z runs have been illustrated. A key to the configurations is laid out in Table I. The main conclusions are summarised as:

a) As found in Clark *et al.* (1997) errors in both mean and RMS show a diurnal pattern insensitive to initialisation time.

i) The *development* (with tiles) version is the closest to zero bias at forecast times less than T+15.

ii) The previously observed maxima in RMS errors at 08Z and 14Z are reduced in the *development* (with tiles) version by up to 0.2K. However the general overnight increase in RMS errors is still observed.

b) There is little variation in either bias or RMS between all the version and configurations.

i) The *development* (with tiles) version improves the bias over the APM up to T+4 by 0.2-0.3K irrespective of initialisation time

The most interesting indicator of the performance of the *development* (with tiles) version is the overall relative comparison with the *first trial* configurations and the APM. This is shown below in Table II as the bias and RMS errors in daily maximum and minimum screen temperature forecasts. Since the available forecast period was limited, these statistics have been calculated using the following procedure: The maximum screen temperature was derived from the 00Z run by taking the daily maximum as the maximum hourly forecast value between 06Z and 18Z. This was then compared with the maximum hourly value observed over the same period. Similarly, the minimum was taken from the 12Z forecast as the minimum forecast screen temperature between 18Z and 06Z. The data covered the period 1-11-96 to 30-11-96.

The results show the gross impact of implementing the tile surface exchange scheme within

the SSFM to form its *development* version. Namely, a reduction of about 0.3K in the cold bias of the daily maximum together with a 0.2-0.3K improvement in RMS error. The slight warm bias in the nighttime minimum is increased largely due to the influence of the canopy scheme as discussed earlier in the section on idealised performance. The RMS error is comparable with the other configurations including the APM.

Table II

Model Configuration	Maximum screen temperature		Minimum screen temperature	
	Bias (K)	RMS (K)	Bias (K)	RMS (K)
M00000 As per mesoscale (APM)	-1.103	1.495	0.292	1.608
S00093 *first trial* (1): MOSES + MO surface exchange + 9 soil levels	-1.188	1.685	0.977	2.077
S00095 *first trial* (2): MOSES + MO surface exchange + 9 soil levels + vegetation canopy	-1.028	1.516	0.127	1.522
S00159 *development*: Tiles + MOSES +MO surface exchange + vegetation canopy	-0.752	1.321	0.547	1.660

Screen Temperature - 12Z initialisation

Integrations from the 12Z run were focused in upon as they provide sufficient time for the model to initialise from the MES and to develop the boundary layer through its own physics before evening transition takes place.

a) The general increase in negative bias observed in the *first trial* (no tiles) configurations by Clark *et al.* (1997) at T+4 has been reduced, but not eliminated, in the *development* (with tiles) version by 0.2-0.6K making it comparable in magnitude to the APM. It must be noted that the 0.3K decrease, compared to the APM, in the negative bias in the *development* version prior to T+4 makes the subsequent increase appear relatively bad. This effect is associated with the evening transition period and points to errors in the surface exchange and boundary layer parametrizations present in both the current and tiled schemes.

b) Between T+4 and T+18 there is a change in bias towards zero, crossing zero between T+9 and T+15 depending upon configuration. During this period the *development* version shows a constant positive offset in bias of about 0.2K with respect to the APM.

c) The RMS errors of all models show an initial convergence to T+3 followed by a linear increase out to about T+7, then a significantly reduced rate of increase out to T+18.

d) The RMS error associated with the *development* version is comparable with the APM up to T+3 but then increases to be 0.1-0.2K larger at subsequent forecast times.

e) The performance of the *development* version compared to the *first trial* configurations is such that it has a lower RMS by about 0.1K than both the configuration with the vegetation canopy (S00093) and that without the vegetation canopy (S00091) up to T+4. Beyond T+4 and up to T+10 the *first trial* configuration without the vegetation canopy out performs the *development* version by about 0.1K, which in turn out performs the configuration without the vegetation canopy by the same degree. After T+10, the *first trial* configuration with the vegetation canopy and the *development* version are comparable but both out perform the *first trial* configuration by about 0.2K.

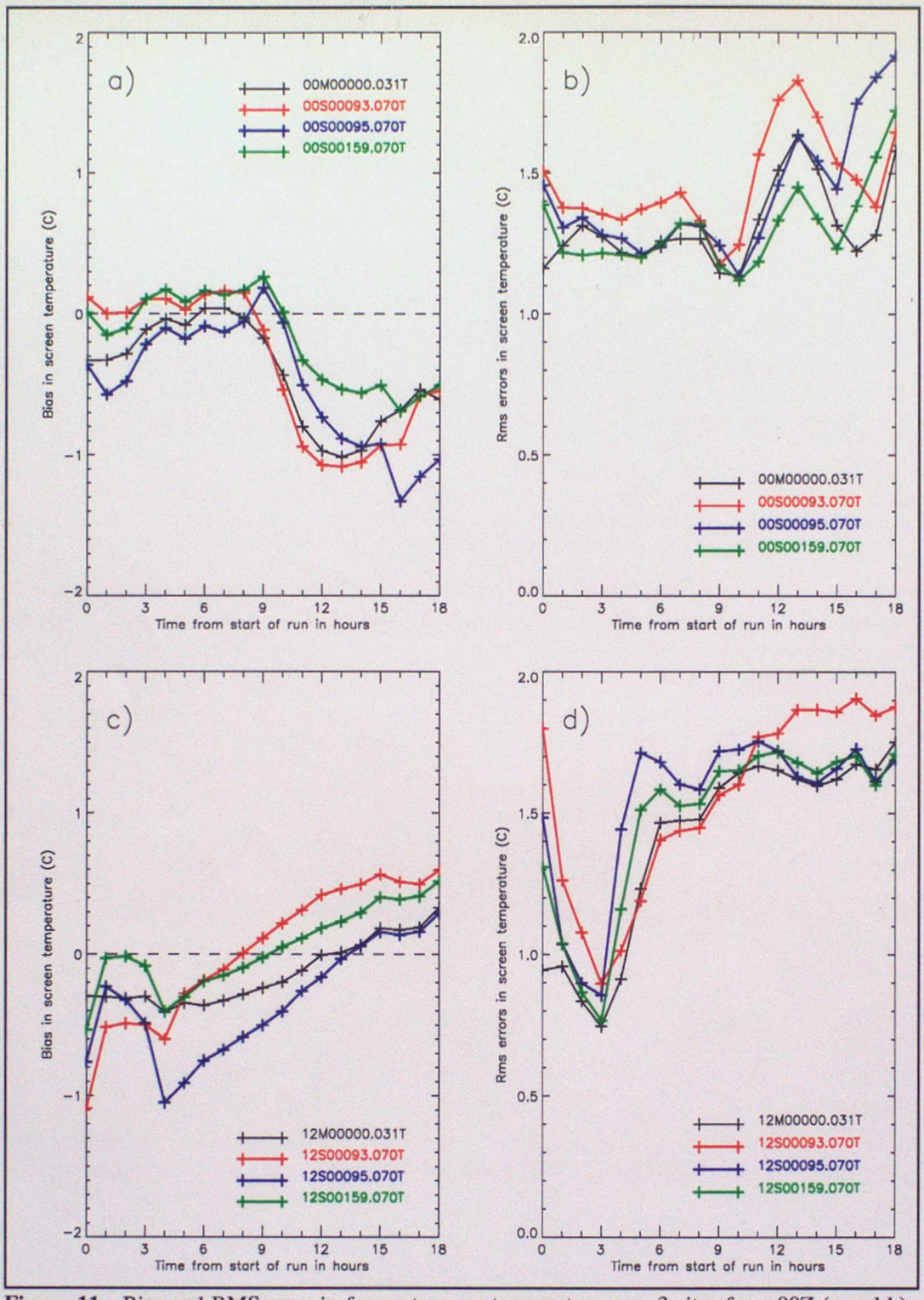

Figure 11 - Bias and RMS error in forecast screen temperature over 3 sites from 00Z (a and b) and 12Z (c and d). See Table I for explanation of the key.

Individual Site Behaviour

Screen Temperature

Again integrations from the 12Z run were focused in upon as they provide sufficient time for the model to initialise from the MES and to develop the boundary layer through its own physics before evening transition takes place.

The results for the individual sites, biases and RMS errors shown in Figures 12 and 13, qualitatively echo the overall performance. Yet the site performance with both the *first trial* (no tiles) and the *development* (with tiles) version mirrors the degree of urbanity as proposed by Clark *et al.* (1997) where the vegetation canopy scheme produces a too rapid surface cooling at the more urban sites. There are varying degrees of bias with forecast time; during the daytime the bias at the more urban sites is improved by about 0.3K in the *development* version whilst after evening transition it divides the *first trial* versions. At the more rural site of Beaufort Park the bias is worsened when compared to the APM by approximately 0.3K during the daytime but relatively recovers towards the end of the forecast period. Despite this at evening transition the *development* version exhibits a desirable (relatively) flat bias response. These results imply that the tile surface exchange scheme, implemented within the *development* version of the SSFM, slightly offsets the increased surface cooling at the more urban sites during evening transition produced by the vegetation canopy scheme. The RMS errors follow the trends shown by the biases.

Again the most interesting indicator of the performance of the *development* version is the overall relative comparison with the *first trial* configurations and the APM for all forecast times. The procedure employed to produce Table II was repeated but on a site-by-site basis with the results shown below in Table III as the bias and RMS errors in daily maximum and minimum screen temperature forecasts. Caution should taken when attempting to compare Figures 12 and 13 and Table III due to the diurnal behaviour of the screen temperature statistics documented earlier. Caveats in mind, the *development* version reduces the cold bias over the rural site of Beaufort Park by 0.2-0.3K whereas the more urban site of Heathrow is also reduced by 0.3-0.5K with the mixed site of Gatwick being somewhere in between.

Table III

Model Configuration	Maximum screen temperature		Minimum screen temperature	
	Bias (K)	RMS (K)	Bias (K)	RMS (K)
	3763 3772 3776	3763 3772 3776	3763 3772 3776	3763 3772 3776
M00000 As per mesoscale (APM)	-0.549 -1.606 -1.154	1.079 1.844 1.482	0.889 -0.434 0.422	1.771 1.652 1.428
S00093 *first trial* (1): MOSES + MO surface exchange + 9 soil levels	-0.524 -1.671 -1.369	1.177 1.985 1.807	1.466 0.208 1.258	2.132 1.513 2.510
S00095 *first trial* (2): MOSES + MO surface exchange + 9 soil levels + vegetation canopy	-0.395 -1.519 -1.171	1.078 1.789 1.600	0.685 -0.627 0.322	1.574 1.668 1.348
S00159 *development*: Tiles + MOSES +MO surface exchange + vegetation canopy	-0.180 -1.172 -0.905	1.109 1.468 1.384	1.189 -0.309 0.759	1.869 1.534 1.599

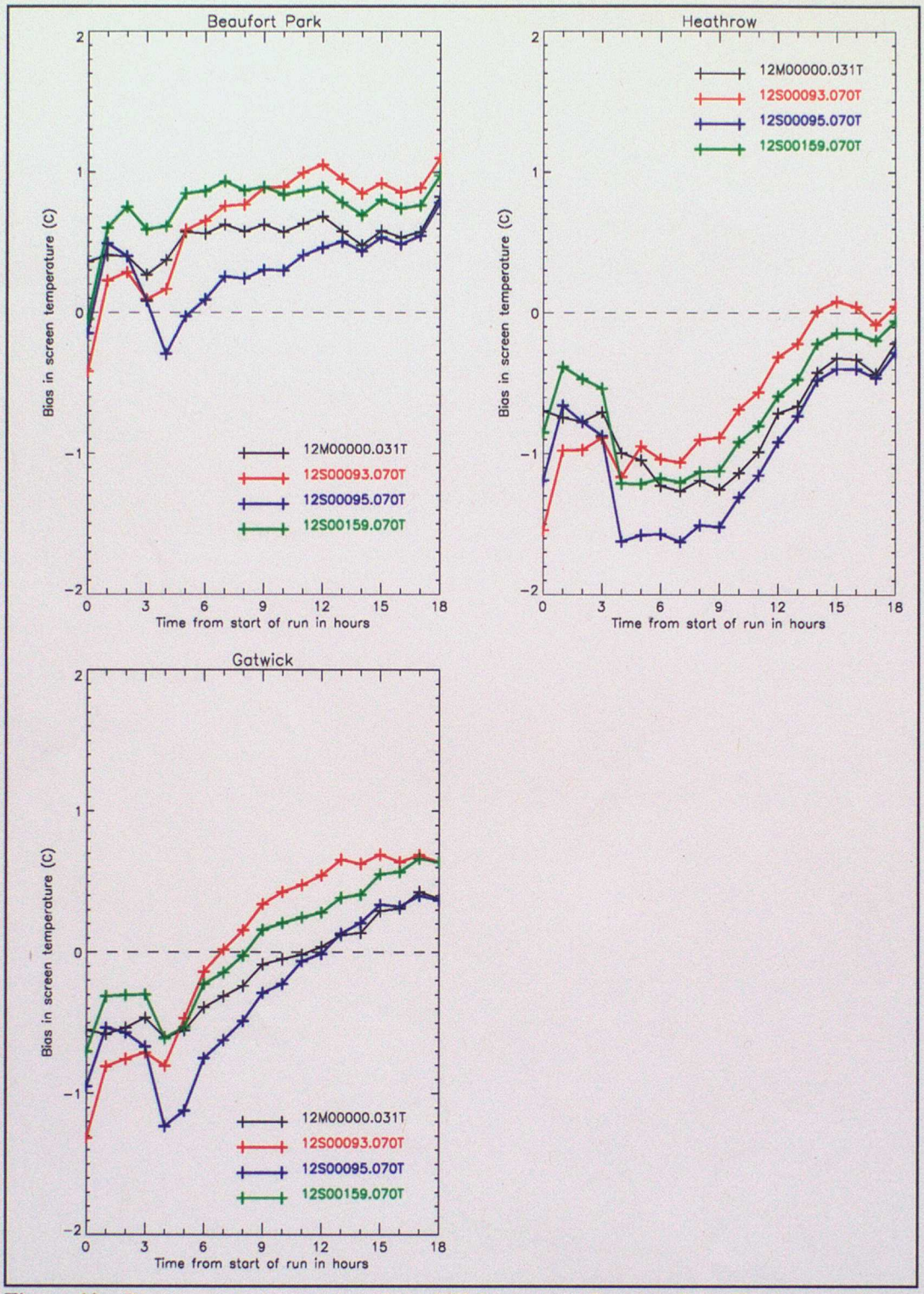

Figure 12 - Bias in screen temperature from 12Z forecasts at Beaufort Park, Heathrow and Gatwick. See Table I for explanation of the key.

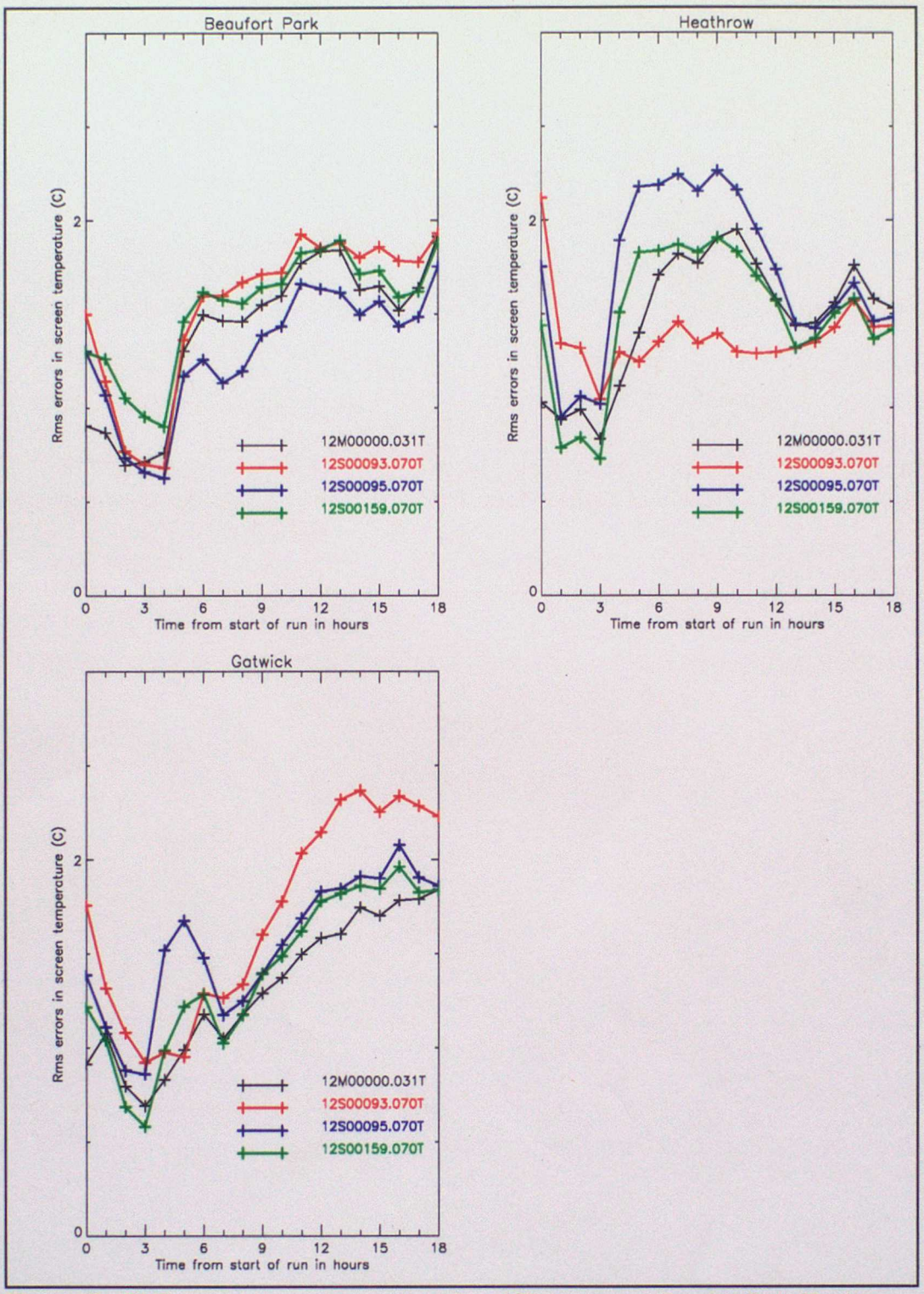

Figure 13 - RMS errors in screen temperature from 12Z forecasts at Beaufort Park, Heathrow and Gatwick. See Table I for explanation of the key.

Tile Screen Temperature - development version only

The previous subsections have intercompared the diagnosed screen temperature from the *first trial* (no tiles) configurations with a consistent grid-box diagnosed screen temperature from the *development* version. It can be argued that the most appropriate screen temperature diagnostic is the one derived over a grass surface as observing sites on the whole tend to be in grass enclosures. However, this temperature may not be the most representative as, for example, a grass enclosure of approximate size $10m^2$ may be surrounded by a surface other than short grass. Hence for some sites the screen temperature over the surface immediately upwind (if known) may be more representative or an aggregate of an upwind surface and grass enclosure. For Heathrow and Gatwick the UKMO enclosures have urban and tree surfaces respectively in the wind directions that dominated in this trial. The Beaufort Park site, although surrounded by trees, has approximately 500m expanse of grass between the enclosure and the trees in the prevalent wind direction during the trial. Therefore one could anticipate that for the chosen sites in November 1996 the most appropriate screen temperature would be that diagnosed over urban and trees for Heathrow and Gatwick respectively, plus a mixture of grass and trees for Beaufort Park.

The separate tile screen temperature results, bias and RMS error, for the individual sites are shown in Figures 14 and 15 from 12Z forecasts. The composition of each tile is described in Table IV below together with proportion of each tile surface associated with each site.

Table IV

Tile Number	Proportion (%)			Tile Description
	3763	3772	3776	
1	35	0	0	Broadleaf Trees
2	35	0	17	Needleleaf Trees
3	20	50	45	C3 grass
4	0	0	0	C4 grass
5	0	0	12	Bare soil
6	10	50	20	Urban
7	0	0	0	Open water

a) The biases for all tiles at all sites are of similar magnitude up to T+3 due to the continuing impact of the initialisation. At this point their magnitude is of the same order as the grid-box screen temperature bias in Figure 12, a warm bias of about 0.3K over the APM. Beyond T+3 the tile biases diverge to form three distinct groups whose evolution is site dependent. These groups consist of i) tree-like tiles, ii) grass-like tiles and bare soil-like tiles.

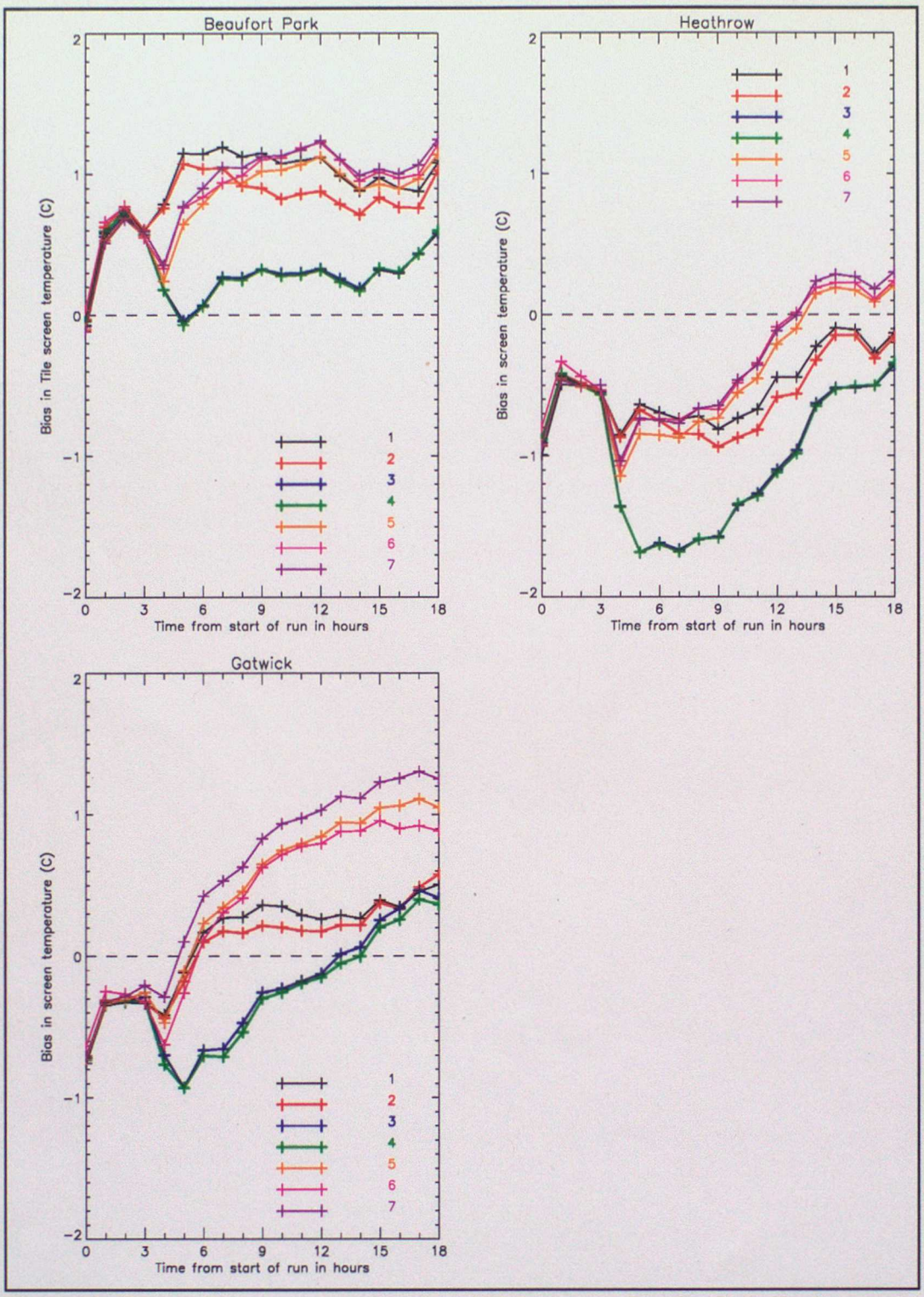

Figure 14 - Bias in tile screen temperature from 12Z forecasts at Beaufort Park, Heathrow and Gatwick. For explanation of tiles see Table IV.

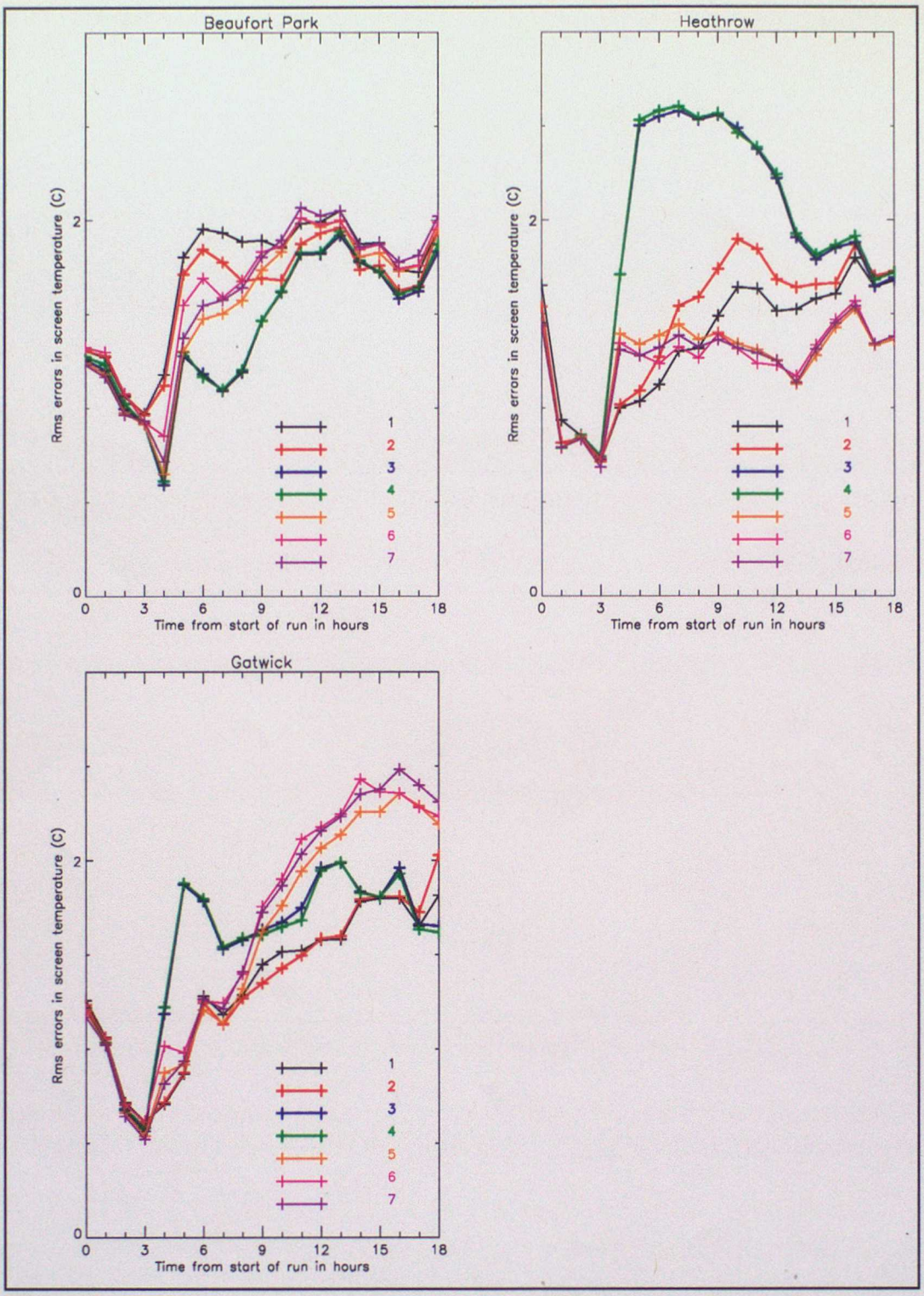

Figure 15 - RMS errors of tile screen temperatures from 12Z forecasts at Beaufort Park, Heathrow and Gatwick. For explanation of tiles see Table IV

b) For Beaufort Park the tree-like and bare soil-like tile screen temperatures linearly increase out to T+5 in line with the grid-box bias and the bias in the APM. Beyond T+5 these groupings flatten off showing a constant warm bias of 0.3-0.4K with respect to the APM. The grid-box bias follows this trend due to the large total proportion of trees and urban (80%) in the land-use. However, the warm bias for the grass-like tiles decreases after T+3 to close to zero at T+5 subsequently increasing to 0.2-0.3K by T+7 where upon it remains flat for the rest of the forecast period. This is a reduction in warm bias of 0.3-0.4K over the APM and a 0.6-0.7K reduction in warm bias when compared to diagnosed grid-box screen temperature bias. The above qualitative behaviour is also apparent in the RMS errors with decreases of about 0.1K over the APM and 0.2-0.5K over the grid-box due to improvement around evening transition. Therefore the diagnosed screen temperature over a grass surface would give most improvement in bias and RMS errors despite the surface being 80% trees and urban.

c) For Heathrow, beyond T+3, the grass-like tiles show a large initial increase in cold bias to -1.7K at T+5 which linearly reduces to about -0.3K by T+18. The tree-like and bare soil -like tiles have an initially flat cold bias after T+3 before it linearly decreases with forecast time beyond T+9 with different rates. The bare soil-like tiles crossing zero bias at T+13 to give a flat, slightly warm bias for the rest of the forecast period. The tree-like tiles achieve a minimum cold bias at T+14 it remaining flat afterwards. Comparing with the APM and grid-box biases: the grass-like tiles show an increase in cold bias of 0.2-0.4K and 0.3-0.5K beyond T+3 compared to the APM and grid-box respectively; the tree-like tiles show a decrease in cold bias of 0.2-0.4K and 0.1-0.2K beyond T+3 compared to the APM and grid-box respectively; and the bare soil-like tiles show a decrease in cold bias of 0.5-0.6K and 0.4K compared to the APM and grid-box respectively. The RMS errors show similar qualitative performance enhancement with decreases of 0.2-0.5K over the APM and 0.3-0.6K over the grid-box value if the bare soil-like tiles are selected. Here there is particular improvement in the RMS errors during the period of evening transition. Therefore the diagnosed screen temperature over a bare soil/urban surface would be most appropriate in terms of bias and RMS error for this site.

d) For Gatwick, after T+3, the grass-like tiles show an initial increase in cold bias to about 1K by T+5. This subsequent decreases linearly with forecast time crossing zero bias at T+12 and becoming a net positive bias of 0.4K by the end of the forecast period. The tree and bare soil-like tiles show a comparable linear decrease in cold bias between T+3 and T+6 crossing zero bias at T+5. From here onwards they diverge with the bare soil-like tiles continuing to increase their warm bias tending to warm biases of between 0.9K and 1.1K by the forecast end; the bias in the tree-like tiles flattens at T+7 producing a constant warm bias of about 0.2-0.3K for the rest of the forecast period. Comparing with the APM and grid-box bias both are more tree or bare soil-like than grass-like. At T+6 the grass-like tile has a cold bias of 0.3K and 0.6K compared to the APM and gird-box values respectively decreasing to 0.1K and 0.3K by the end of the period for APM and grid-box respectively. This implies that choosing a grass-like tile only improves the bias when compared to the APM or grid-box value after T+14. The bare-soil like tiles, after T+4, always have a warm bias of 0.3-0.7K and 0.3-0.5K when compared to the APM and grid-box values respectively. This is only a benefit, i.e. a net reduction in bias, between T+4 and T+5. However the tree-like tiles are warm biased, when compared to the APM and grid-box, prior to T+15 for the APM and T+8 for the grid-box and cold bias afterwards. In net terms the bias in the tree-like tiles is beneficial for T+3 to T+7

and T+15 to the period end when compared to the APM and for T+3 to T+6 and T+8 to the period end when compared to the grid-box. This performance is again mirrored, to a lesser degree, in the RMS errors with decreases of 0.1-0.2K over the APM and 0.2-0.3K over the grid-box being typical if the tree-like tiles are selected. Therefore the diagnosed screen temperature over a tree surface would be the most appropriate in terms of bias and RMS error for this site.

To summarise runs initialised at 12Z, all three sites choosing to diagnose the site screen temperature over a tile that is representative of the dominant surface immediately upwind of the observation site produces the best objective verification, both in terms of bias and RMS error. In this statement the Beaufort Park result has been included despite appearing contrary to the instinct that the large fraction of trees that encircles this site (a clearing approximately 100m by 500m) should provide the dominant influence in diagnosing the characteristic screen temperature. Revisiting Figures 14 and 15 one can see that the improvement in bias and RMS error resulting from choosing the grass tile is confined to after evening transition; the run being initialised from 12Z as discussed earlier; where the near surface flow over the grass within the clearing has become statically stable more rapidly than the flow over the surrounding trees. This static stability enhanced by sheltering provided by the surrounding trees will influence the observations made at this site biasing them towards the grass surface maintained within the clearing. Later on into the night the flow over the surrounding trees also stabilises allowing energy, stored during the daytime, to be released by the tree canopy. This prevents further cooling in the clearing giving the model an increasing cold bias over the grass tile since this effect is not modelled within the tile scheme. Hence, in hindsight, one might expect a grass tile to provide the best verification results in stable nighttime conditions formed immediately after evening transition but the trees tiles or some combination of them with the grass may be more satisfactory later on in the might towards the time of minimum temperature.

A further assessment of performance can be obtained by deriving the overall relative performance on a site-by-site basis for each of the tiles in the *development* version of the SSFM. This employs a similar method to that used to generate Table III. The results are shown below in Table V as the bias and RMS errors in daily maximum and minimum tile screen temperature forecasts.

The sites, except for Beaufort Park, show no diurnal variation in tile suitability for screen temperature diagnosis. The Beaufort Park result confirms the discussion above, with the bias and RMS errors in maximum temperature being representative of an aggregate of upwind surfaces (trees, grass, urban) due to the well mixed nature of the daytime boundary layer, and the nighttime minimum temperature being representative of the grass surface that exists within the clearing at Beaufort Park due to the enhanced stable flow that exists within it. A later paper will discuss a formulation for deducing tile suitability using a source area approach.

Table V

Surface Tile No. and Type	Maximum screen temperature		Minimum screen temperature	
	Bias (K)	RMS (K)	Bias (K)	RMS (K)
	3763 3772 3776	3763 3772 3776	3763 3772 3776	3763 3772 3776
1 Broadleaf Trees	-0.195 -1.227 -0.947	1.129 1.530 1.438	1.397 -0.298 0.694	2.018 1.781 1.765
2 Needleleaf Trees	-0.165 -1.202 -0.922	1.124 1.511 1.427	1.159 -0.419 0.571	1.922 1.907 1.674
3 C3 grass	-0.192 -1.203 -0.918	1.056 1.485 1.375	0.432 -0.913 0.206	1.616 2.058 1.391
4 C4 grass	-0.172 -1.194 -0.916	1.068 1.483 1.381	0.446 -0.917 0.156	1.656 2.099 1.359
5 Bare soil	-0.209 -1.213 -0.909	1.048 1.491 1.361	1.421 0.170 1.450	2.041 1.423 2.292
6 Urban	-0.143 -1.136 -0.864	1.101 1.451 1.381	1.547 0.263 1.337	2.122 1.457 2.303
7 Open Water	-0.207 -1.210 -0.869	1.028 1.482 1.317	1.539 0.270 1.636	2.129 1.448 2.416

10m Windspeed and Direction

Figures 16 and 17 show the 10m windspeed bias and RMS errors for the three sites:

a) For the biases, the best *first trial* (no tiles) configurations are consistently 1-1.5m/s greater than the APM for all sites, as discovered in Clark *et al.* (1997). The *development* (with tiles) version improves the bias over the APM at Beaufort Park by about 0.4m/s at T+1 to 0.8m/s at T+18; for Heathrow and Gatwick there is a 0.3m/s improvement during the daytime with little or no benefit over the APM beyond T+3.

b) For the RMS errors, the best *first trial* configurations are about 0.3-1.0m/s greater than the APM. The *development* version improves the RMS error by about 0.3m/s over the APM at Beaufort Park; for Heathrow and Gatwick there is a small improvement during the daytime but is consistent with the APM beyond T+3.

Figures 18 and 19 show the 10m wind direction bias and RMS errors for the three sites:

a) For the biases, all versions and configurations closely follow the APM performance with biases of around 10-15 degrees. It was noted by Clark *et al.* (1997) that significant differences in the bias occurred between the APM and the MES suggesting that comparison of results with the APM was not akin to comparison with the MES performance.

b) For the RMS errors, all version and configurations closely follow the APM performance with errors of about 60-70 degrees comparable with the MES errors reported by Clark *et al.* (1997).

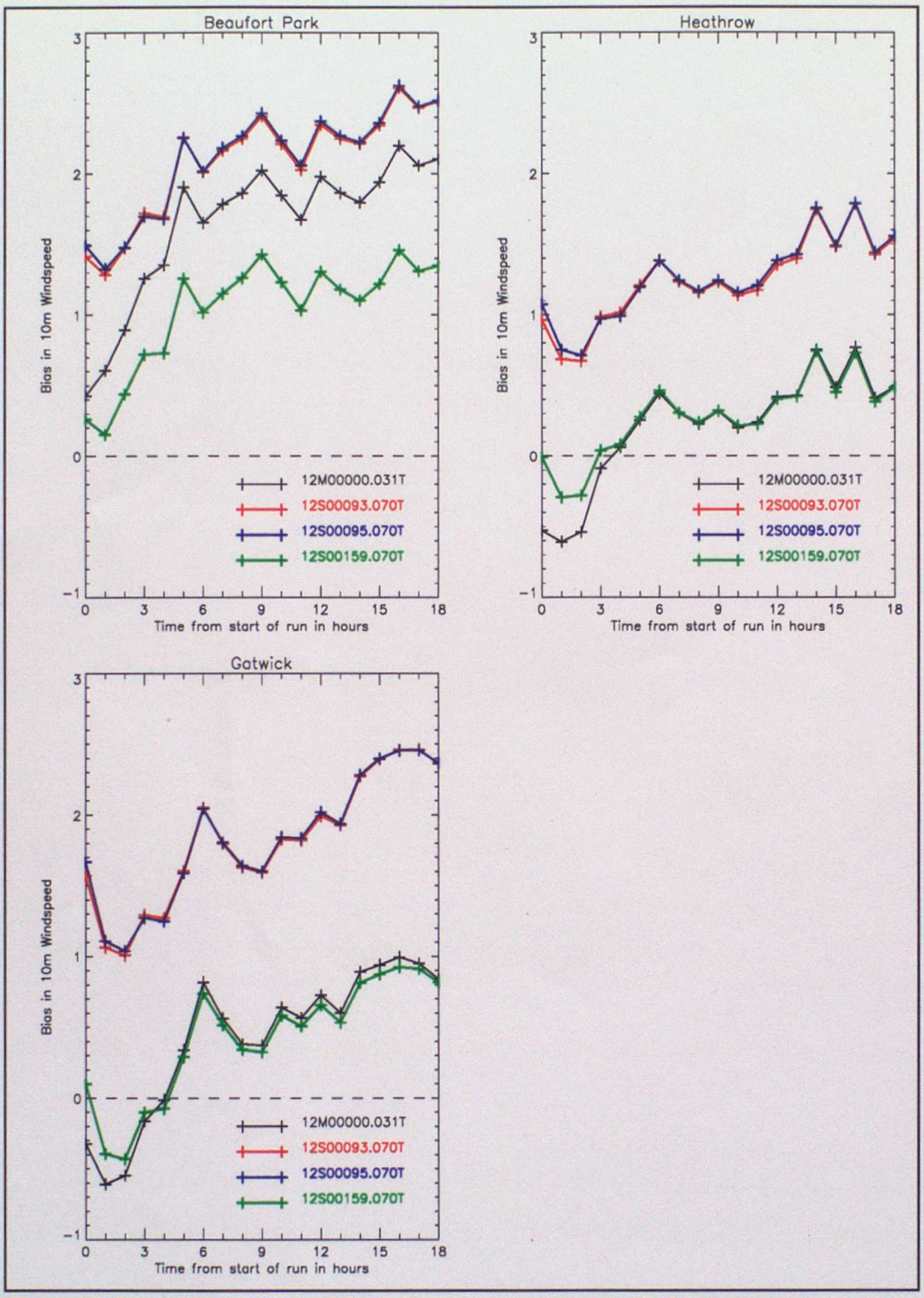

Figure 16 -Bias in 10m windspeed form 12Z forecasts at Beaufort Park, Heathrow and Gatwick. See Table I for explanation of the key

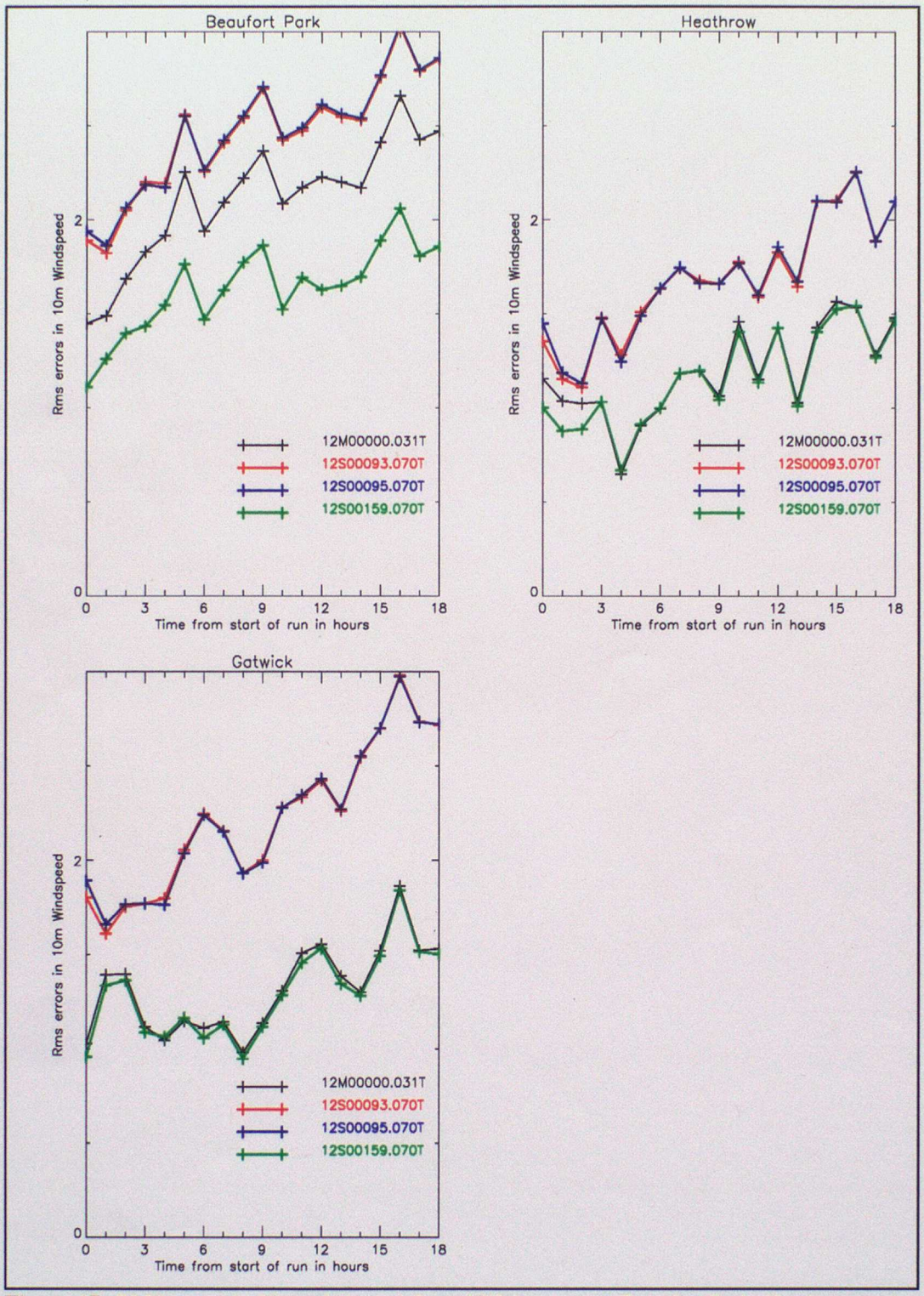

Figure 17 -RMS errors in 10m windspeed from 12Z forecasts at Beaufort Park, Heathrow and Gatwick. See Table I for explanation of the key.

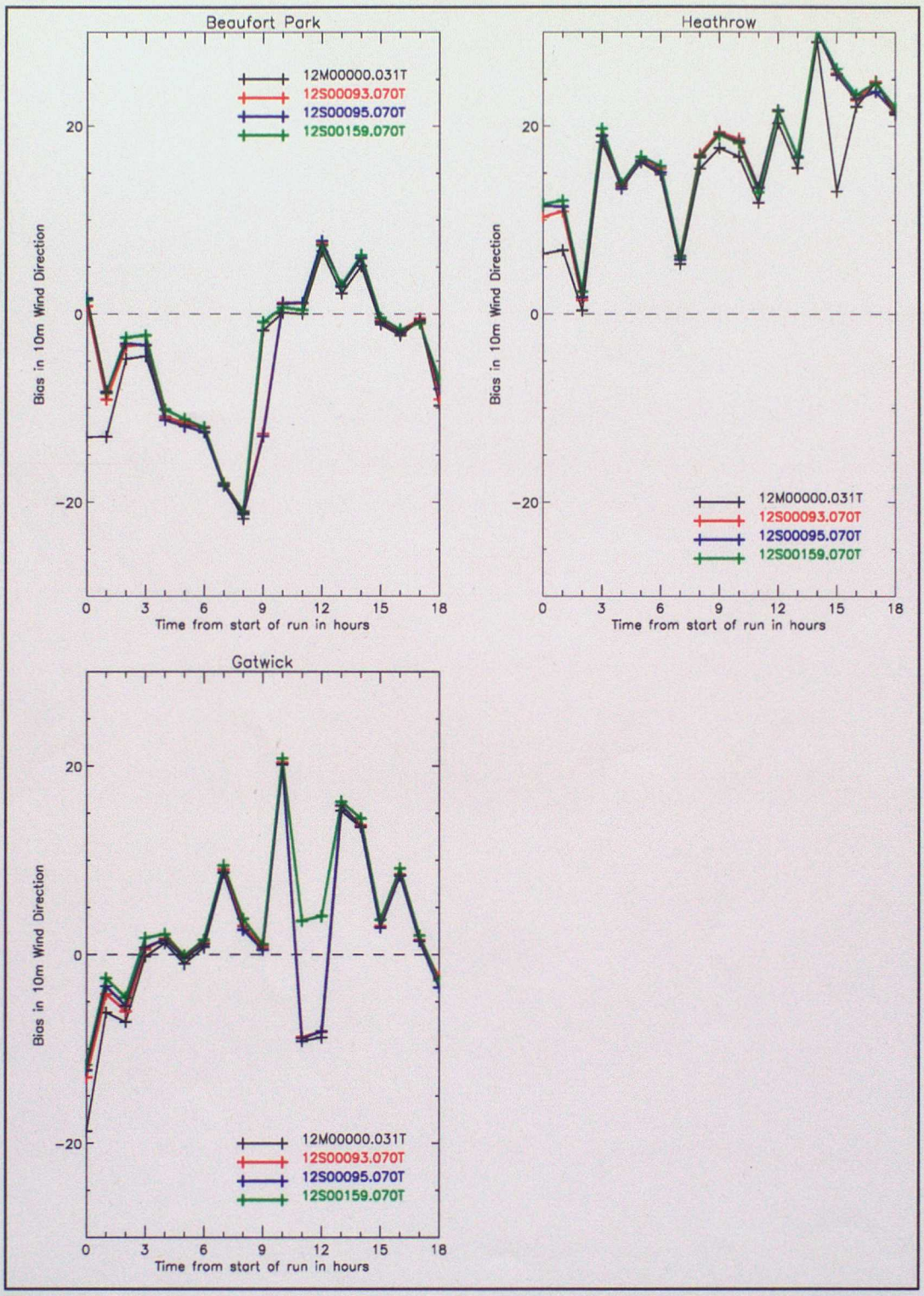

Figure 18 - Bias in 10m wind direction from 12Z forecasts at Beaufort Park, Heathrow and Gatwick. See Table I for explanation of the key.

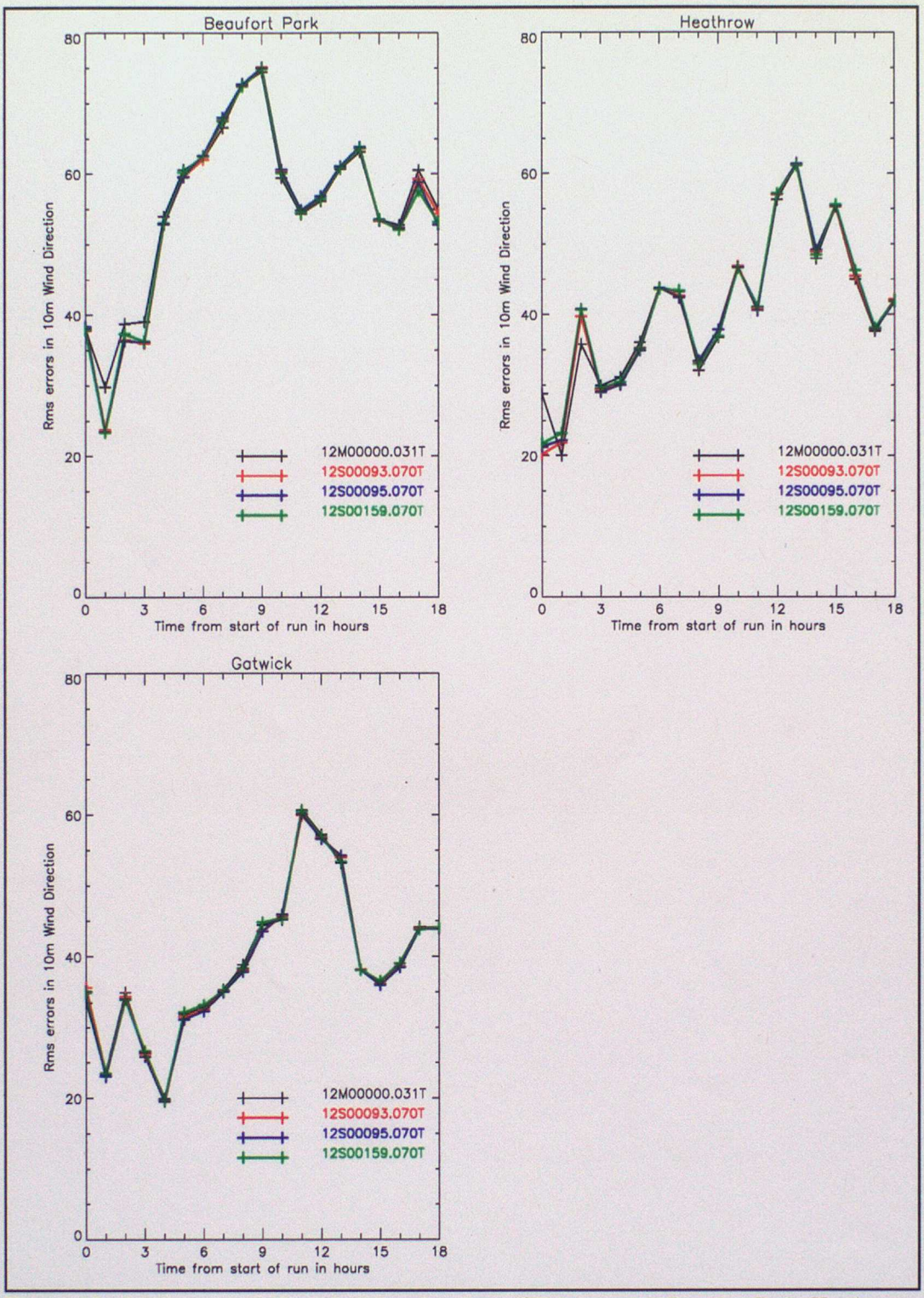

Figure 19 - RMS errors in 10m wind direction from 12Z forecasts at Beaufort Park, Heathrow and Gatwick. See Table I for explanation of the key.

Screen Relative Humidity

Figures 20 and 21 show the screen relative humidity bias and RMS errors for the three sites:

a) The results for Heathrow and Gatwick show a decrease in moist bias of 2-5% and 1-4% over the APM and *first trial* (no tiles) configurations respectively for forecast times up to T+12 where the zero bias axis is crossed. Beyond this the *development* version shows a dry bias compared to all the other configurations. However at Beaufort Park a similar performance invokes a dry bias of 1-5% with forecast time due to the mean bias with forecast time being drier than the other sites. Therefore the effect of introducing tiles is to produce a slightly drier near-surface layer.

b) The RMS errors for all three sites echo the relative performance of the biases.

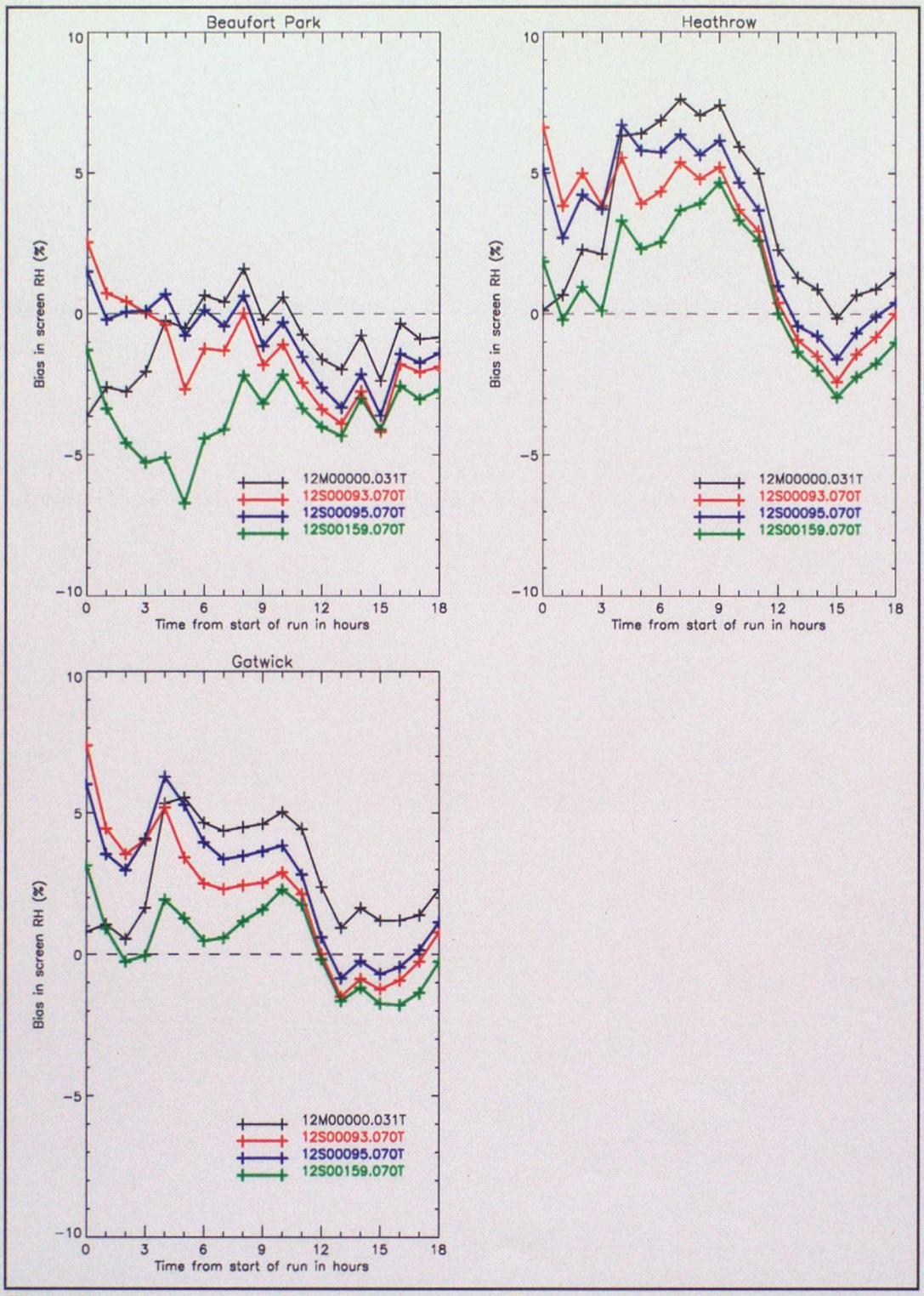

Figure 20 - Bias in screen relative Humidity from 12Z forecasts from Beaufort park, Heathrow and Gatwick. See Table I for explanation of the key.

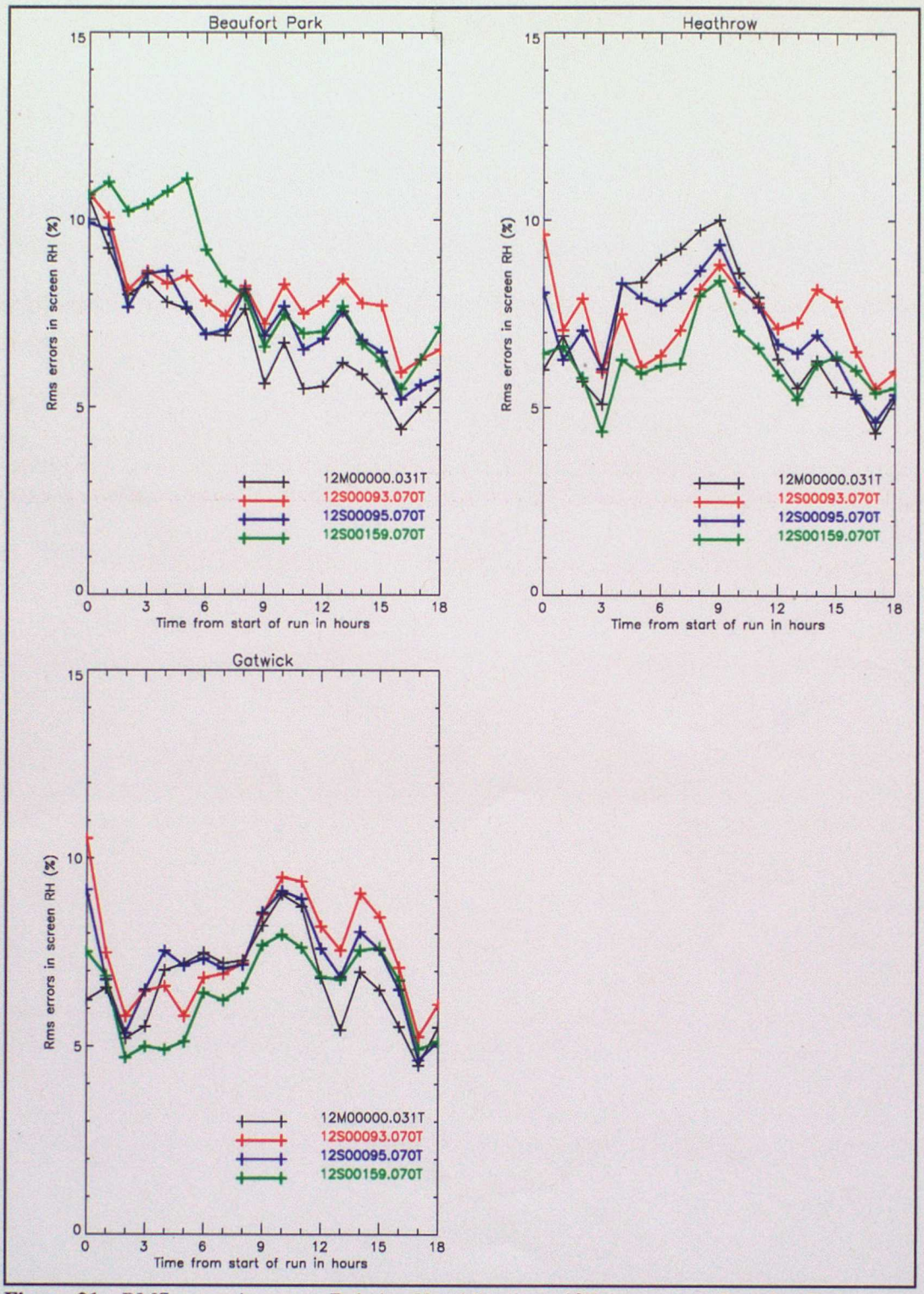

Figure 21 - RMS errors in screen Relative Humidity from 12Z forecasts at Beaufort Park, Heathrow and Gatwick. See Table I for explanation of the key.

Conclusions from Objective Statistics

1) The first objective set at the start of the trial was satisfied, namely that, it has been demonstrated that the tile scheme could be run routinely from coupled mesoscale model data.

2) The diurnal pattern of errors showed that the influence of urban fractions, via the effective thermal inertia of the *soil* surface, in producing a too rapid cooling rate during evening transition has been offset with the implementation of the tile scheme.

3) The impact of evening transition on errors has been reduced but not eliminated by using the tile scheme. This implies errors in the surface exchange and boundary layer mixing that are inherent to both tile and non-tile formulations.

4) In general, the tile scheme reduces the errors in grid-box screen temperature by about 0.3K depending upon the urbaness of the site. Further improvement can be obtained by selecting the surface (or tile) that is most representative of the land-use that is upstream of the observing site. This is particularly true if the grass surface of an observing enclosure is surrounded by a very different surface type.

5) The diurnal nature of the surface representative for diagnosis of the screen temperature needs to be addressed e.g. Beaufort Park. This would involve stability dependency within the choice of most suitable upwind surface.

6) Windspeed and direction errors were reduced with the implementation of the tile scheme as compared to the *first trial* version. The absolute errors became comparable to those of the Mesoscale model suggesting that the tile scheme had correctly parametrized the drag.

Overall Conclusions

The impact of including the tile surface exchange scheme within the *first trial* version to form the *development* version of the SSFM shows clear improvement on the *first trial* version and slight improvement on the Mesoscale Model depending on whether the site is a mostly urban or mostly rural site. This improvement is three-fold:

1) The bias and RMS errors in windspeed have been significantly reduced when compared to the *first trial* version. The bias overspeed was reduced by 1m/s on a previous overspeed of 2m/s and the RMS was reduced by 0.8-1.3m/s on a previous value of 1.8-2.8m/s. Comparison with the APM is good both in terms of bias and RMS errors. It should be remembered that the *development* version contains no description of local orography unlike the APM, and for sites (Beaufort Park) where terrain slopes are small the tile scheme out performs the APM by 0.5m/s in terms of both bias and RMS error for all forecast times compared to previous values of 0.5-1.8m/s and 1.5-2.5m/s respectively.

2) Reduced bias and RMS error in nocturnal grid-box screen temperature by 0.2-0.5K in RMS terms depending on the fraction of urban land-use surrounding the site. Further reductions in mainly bias can achieved by choosing the diagnosed screen temperature most appropriate for the land-use immediately upwind of the site. The magnitude of these improvements is 0.2-0.4K depending again on the fraction of urban land-use surrounding the observation site.

3) Reduced bias and RMS error in daytime grid-box screen temperature by 0.3-0.5K in bias and about 0.2K in RMS error, the magnitude depending on the fraction of urban land-use surrounding the site. As with nocturnal screen temperatures further reductions can be seen by choosing the most appropriate diagnosed screen temperature for the upwind land-use. This gives reductions in overall bias of between 0.1K and 0.5K and reductions of about 0.1K in RMS error.

These significant reductions in RMS error seen in the *development* version over the *first trial* version and modest reductions when compared to the Mesoscale suggest a general improvement in forecast skill.

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